SELECTED HIGHLIGHTS FROM THE ALICE EXPERIMENT AT THE LHC

ALICE

INFN Istituto Nazionale di Fisica Nucleare

ENRICO FRAGIACOMO

INFN – TRIESTE

ON BEHALF OF THE ALICE COLLABORATION

LXX INTERNATIONAL CONFERENCE
NUCLEUS – 2020
11-17 OCTOBER 2020
ONLINE CONFERENCE

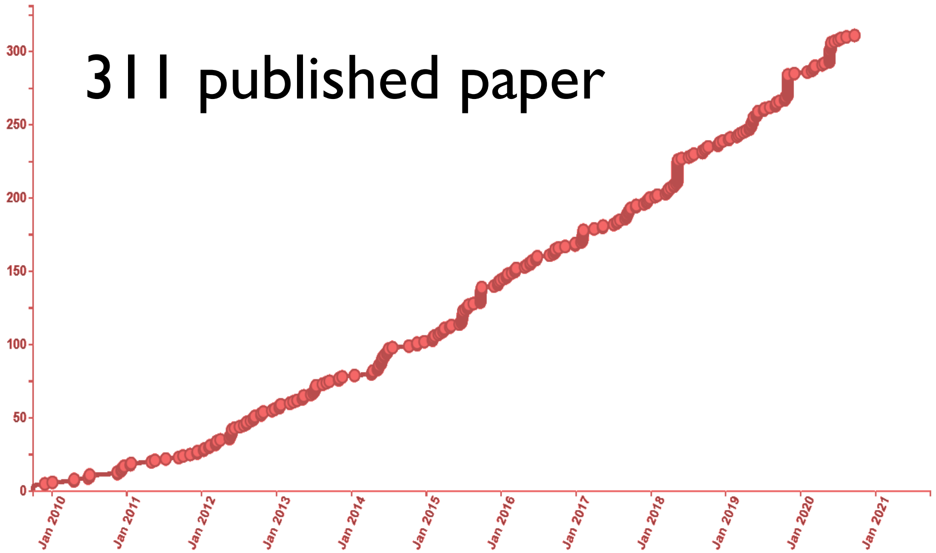
ALICE RESULTS @ NUCLEUS 2020

7 talks and 3 posters

1. Overview of hadron and jet production results from ALICE - Dmitry Yurevich Peresunko
2. ALICE Upgrade for Run 3 and 4 at the CERN LHC - Wladyslaw Henryk Trzaska
3. New Inner Tracking System (ITS) for open charm direct measurements by ALICE at the LHC: status and perspectives - Grigorii Feofilov
4. Latest results on (anti-)hypernuclei production at the LHC with ALICE - Alexander Borissov
5. Measurements of heavy-flavour hadron production with ALICE at the LHC - Cristiane Jahnke
6. The Fast Interaction Trigger for ALICE LHC Run 3 and 4 - Maciej Slupecki
7. [POSTER] Fluctuations of relative yield of the neutral and charged pions in AA collisions in ALICE - Evgeniia Nekrasova
8. [POSTER] Central diffraction and ultra-peripheral collisions in ALICE in Run 3 and 4 - Nazar Burmasov
9. [POSTER] Measurement of the $\Lambda c+$ fragmentation function in pp collisions at sqrt(s)=13TeV with the ALICE experiment - Tatiana Lazareva

THE ALICE COLLABORATION @ LHC

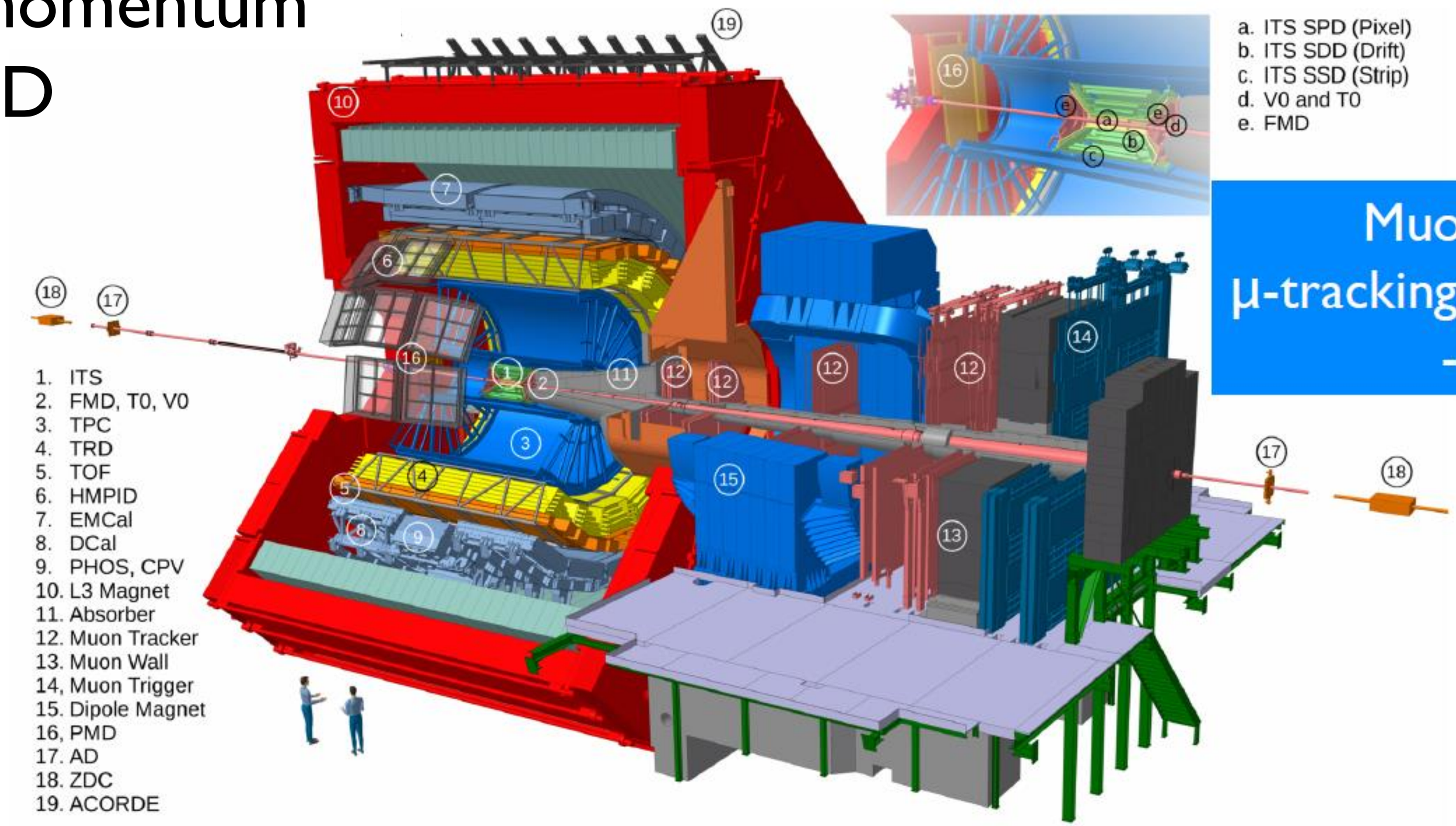
39 countries, 175 institutes, 1025 authors



System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010, 2011 2015, 2018	2.76 5.02	75 μb^{-1} 800 μb^{-1}
Xe-Xe	2017	5.44	0.3 μb^{-1}
p-Pb	2013 2016	5.02 5.02, 8.16	15 nb^{-1} 3 nb^{-1}, 25 nb^{-1}
pp	2009-2013 2015, 2017 2015-2018	0.9, 2.76, 7, 8 5.02 13	200 μb^{-1}, 100 nb^{-1} 1.5 pb^{-1}, 2.5 pb^{-1} 1.3 pb^{-1} 36 pb^{-1}

- Harvest of the past 10 years operation
- Large integrated luminosity in Run 2 allows precise measurements, new observables

Excellent track-momentum resolution and PID



Muon spectrometer
μ-tracking and trigger chambers
$-4 < \eta < -2.5$

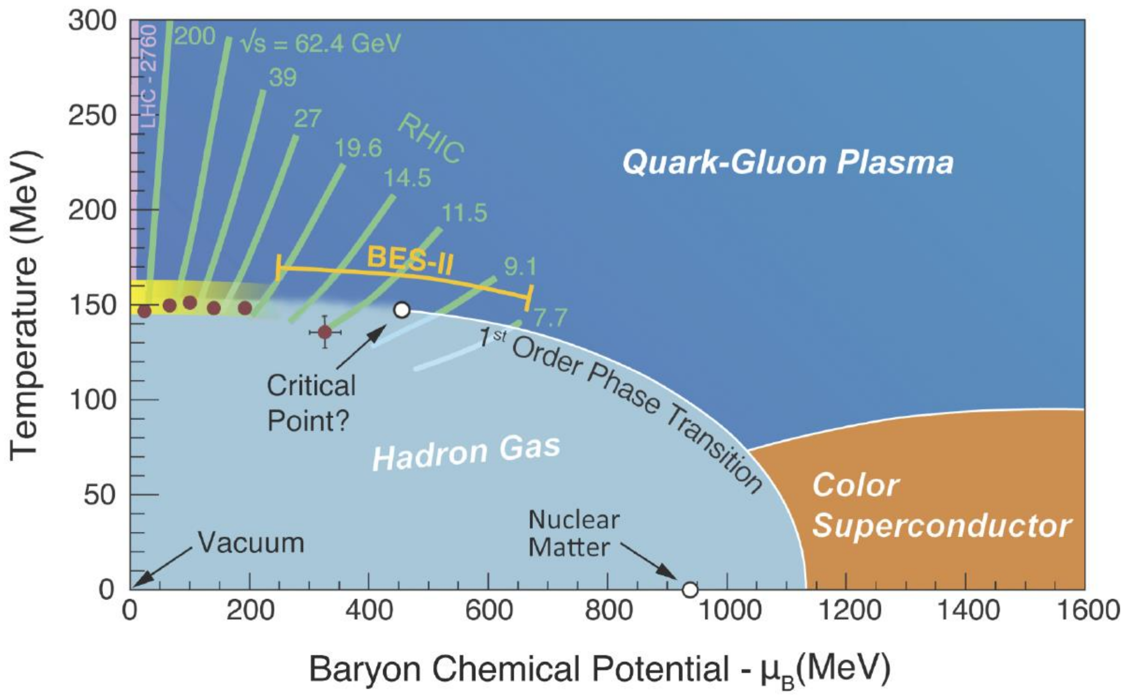
Central barrel:
vertexing, tracking, PID, EM Calos
$|\eta| < 0.9$

Forward detectors:
multiplicity, trigger, centrality, time zero

WHY DO WE STUDY ULTRA-RELATIVISTIC HEAVY-IONS COLLISIONS

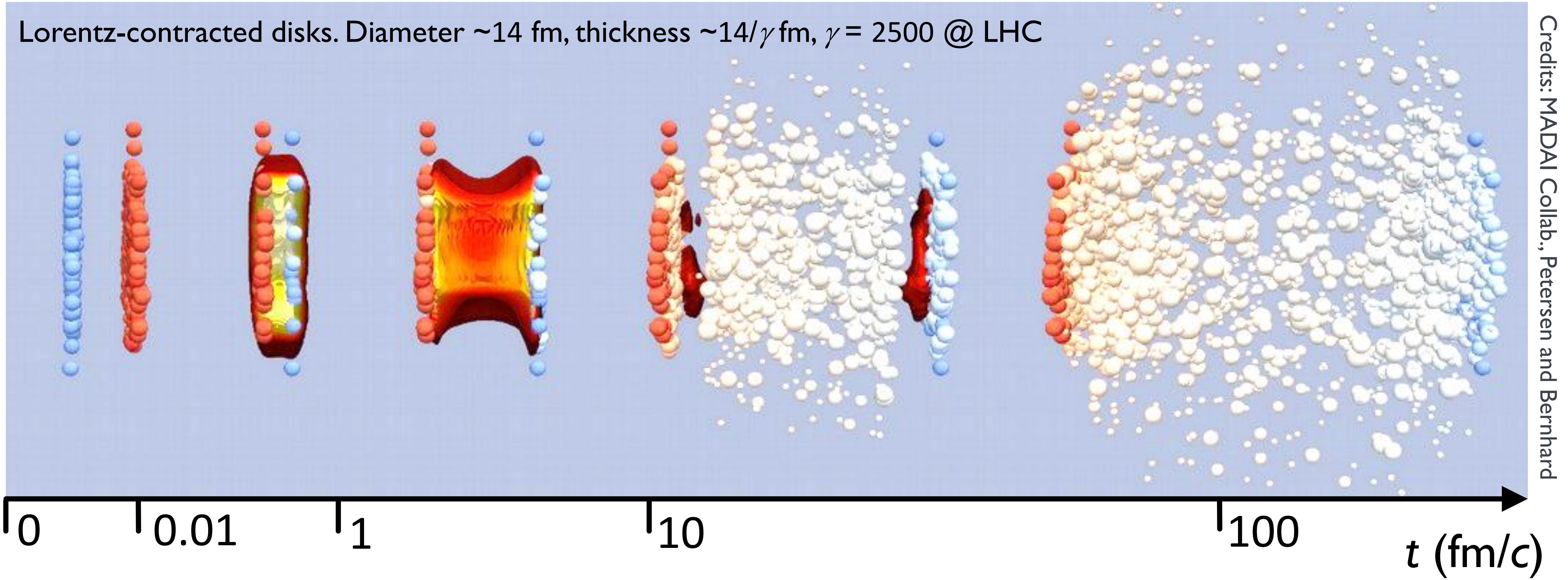
Recreate droplets of primordial matter and study its properties and phase diagram

- In the Early Universe, hadrons emerged from a strongly-interacting quark-gluon plasma (QGP) at $T \sim 150$ MeV (10^{12} K), at a time $t \sim 1$ μsec after the Big Bang
- At hadronization, QGP was a liquid with low shear viscosity η/s. At earlier times it was probably a weakly-coupled plasma of quarks and gluons due to QCD asymptotic freedom.
- At LHC, the transition QGP → hadron phase is a crossover.



- ✓ Open question: how does a hydrodynamic liquid emerge in an asymptotically free gauge theory?
- ✓ Open question: what is the smallest droplet of QGP that can be described using hydrodynamics?

COLLISION EVOLUTION



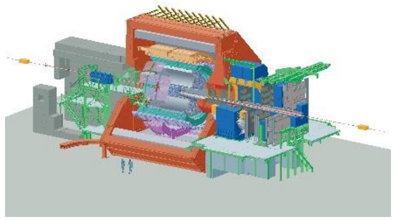
Initial stage
nPDF,
saturation,
shadowing

Gluon and
quark-pair creation
All heavy quarks
created at this stage

QGP: deconfined
nuclear matter
expanding
hydrodynamically

Hadronization and
chemical freeze-out
Inelastic collisions
cease

Kinetic freeze-out
Elastic collisions cease
Free streaming particles
to the detectors



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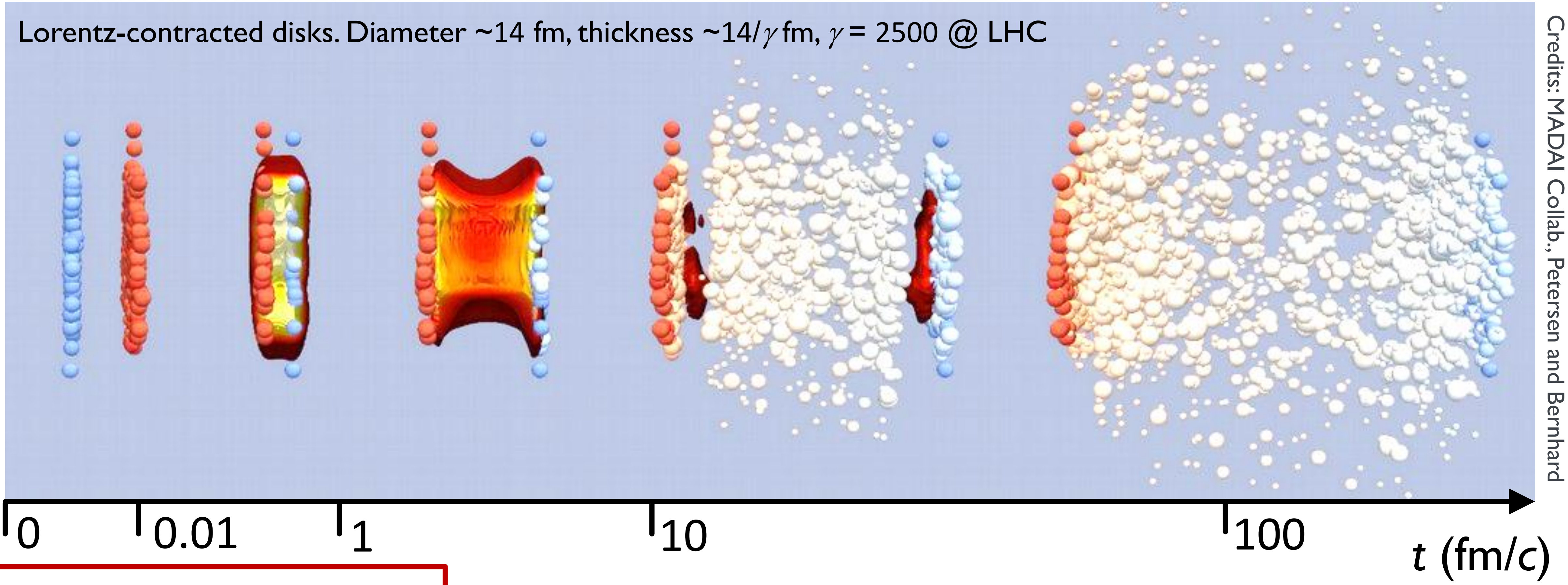

Credits: MADAI Collab., Petersen and Bernhard

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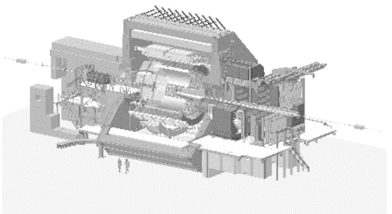
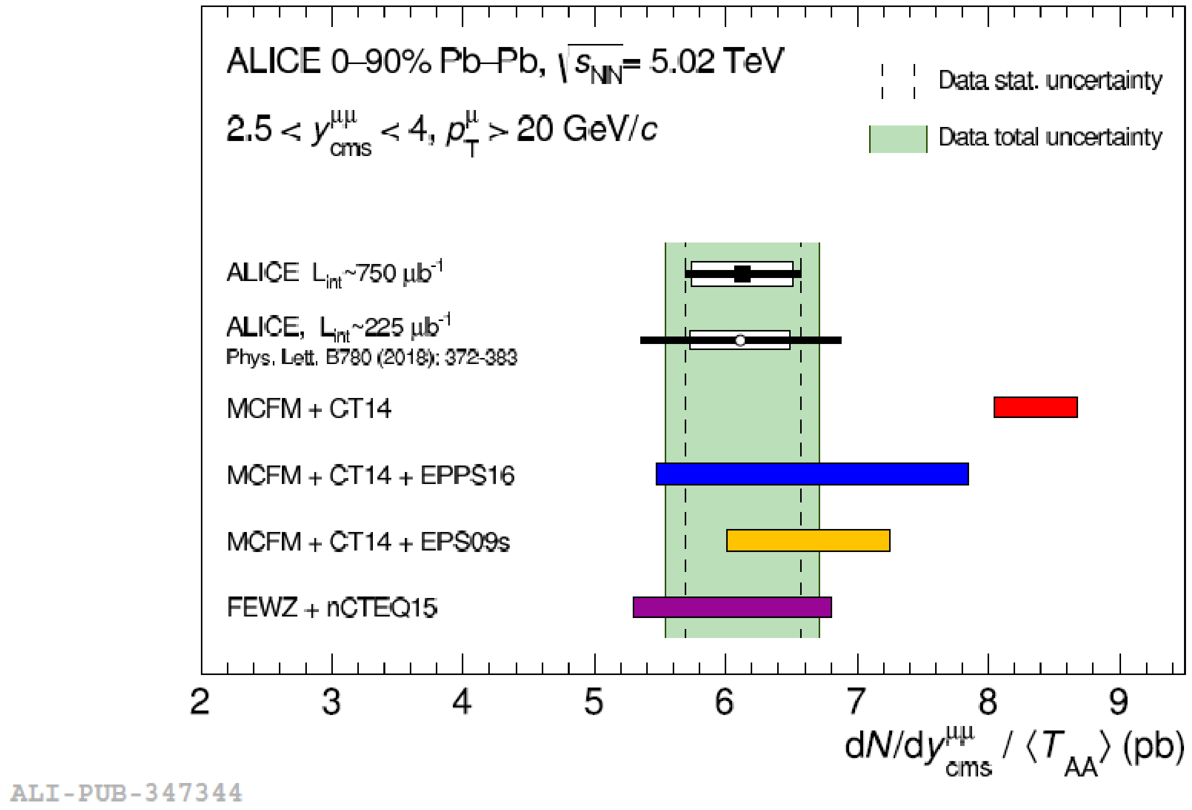


Z AND W MEASUREMENTS CONSTRAIN NUCLEAR PDF

D. Peresunko – 12/10, 16:20

Z and W bosons: sensitive probes of the nuclear modications of the Parton Distribution Functions (PDF):

- production well described by perturbative QCD and electroweak theory
- produced in the hard processes, during the initial stages of the collision
- insensitive to the strongly-interacting medium in their leptonic decay



JHEP 09 (2020) 076

Compatible with calculations including nPDFs using three different models, 3.4 deviation from free PDF prediction with CT14 (previous result: 2.3 deviation)

ENERGY DENSITY IS ESTIMATED FROM MULTIPLICITY DENSITY

High energy density (ε > 1 GeV/fm^3) necessary condition for deconfinement

Energy density from Bjorken's formula

J. D. Bjorken, Phys. Rev. D27, 140 (1983)

τ ~ 0.2 – 0.6 fm/c

$$\epsilon(\tau) = \frac{< m_T >}{\tau\pi R^2}\frac{dN_{ch}}{d\eta}$$

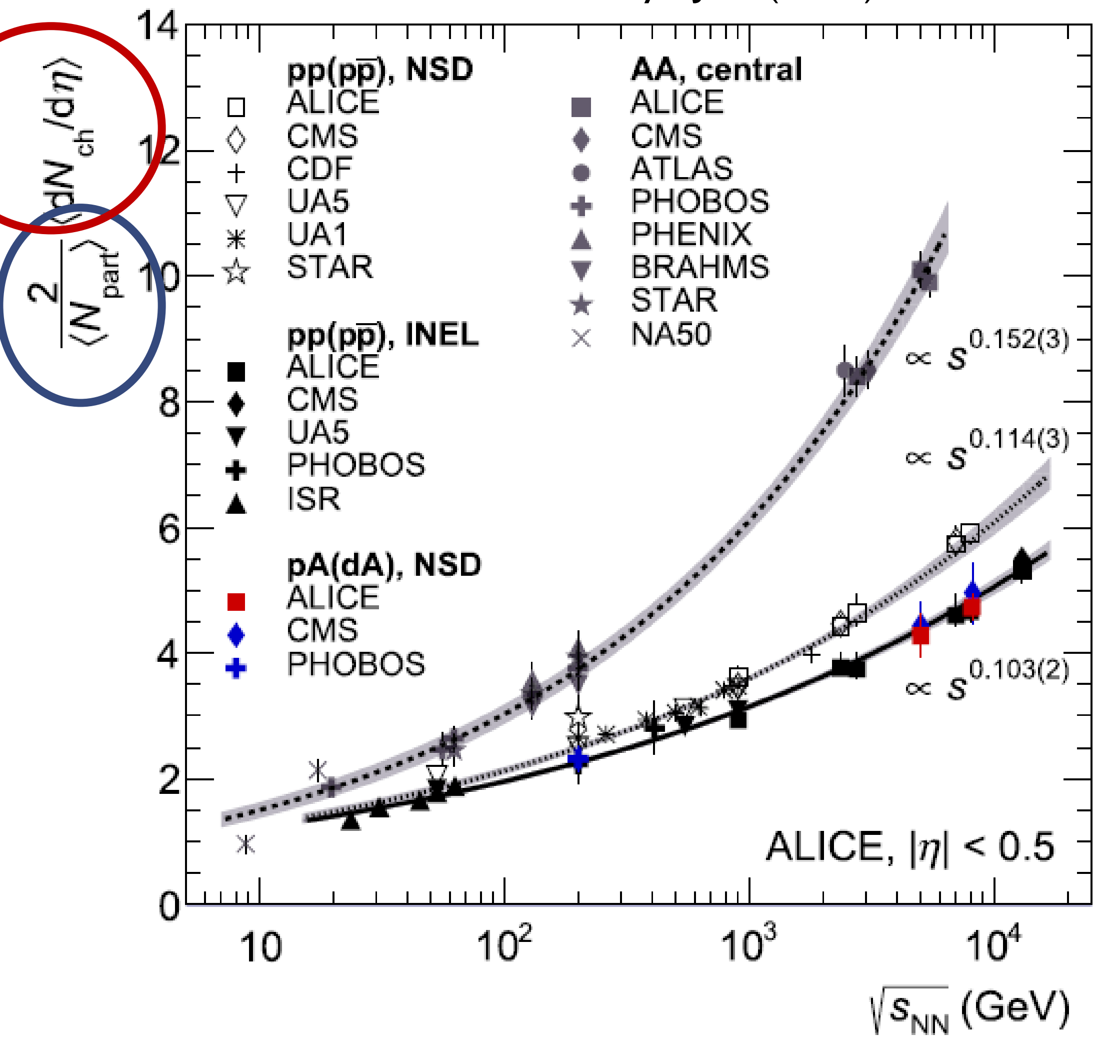
AGS (Au-Au): $\sqrt{s_{NN}}$ = 5 GeV ⇒ ε~1.5 GeV/fm^3

SPS (Pb-Pb): $\sqrt{s_{NN}}$ = 17 GeV ⇒ ε~2.9 GeV/fm^3

RHIC(Au-Au): $\sqrt{s_{NN}}$ = 200 GeV ⇒ ε~5.4 GeV/fm^3

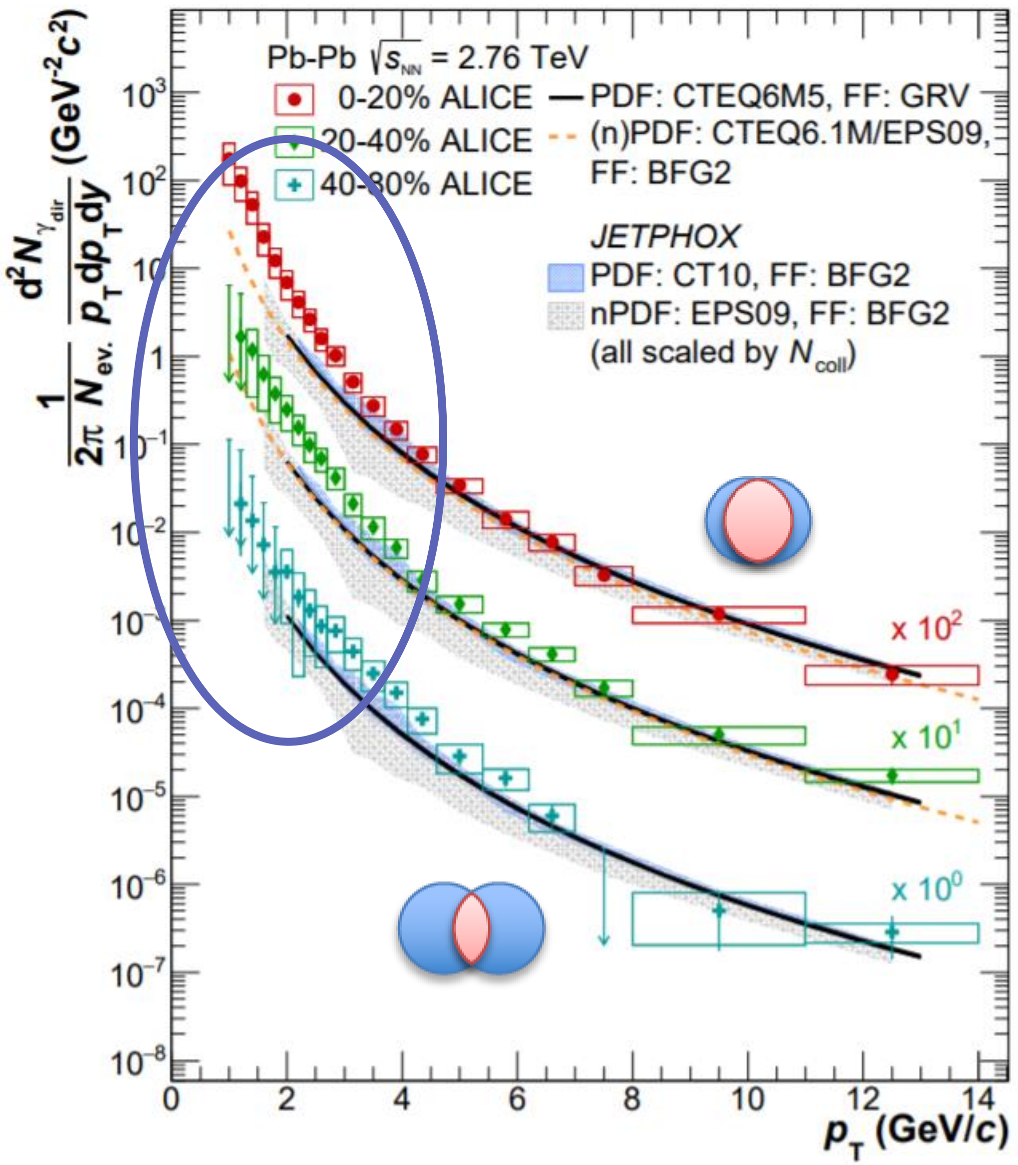
LHC (Pb-Pb): $\sqrt{s_{NN}}$ = 5020 GeV ⇒ ε~18 GeV/fm^3

ALICE Collab., Eur. Phys. J. C (2019) 79:307



Participant: Nucleon that collides with at least one other nucleon

TEMPERATURE FROM DIRECT PHOTONS



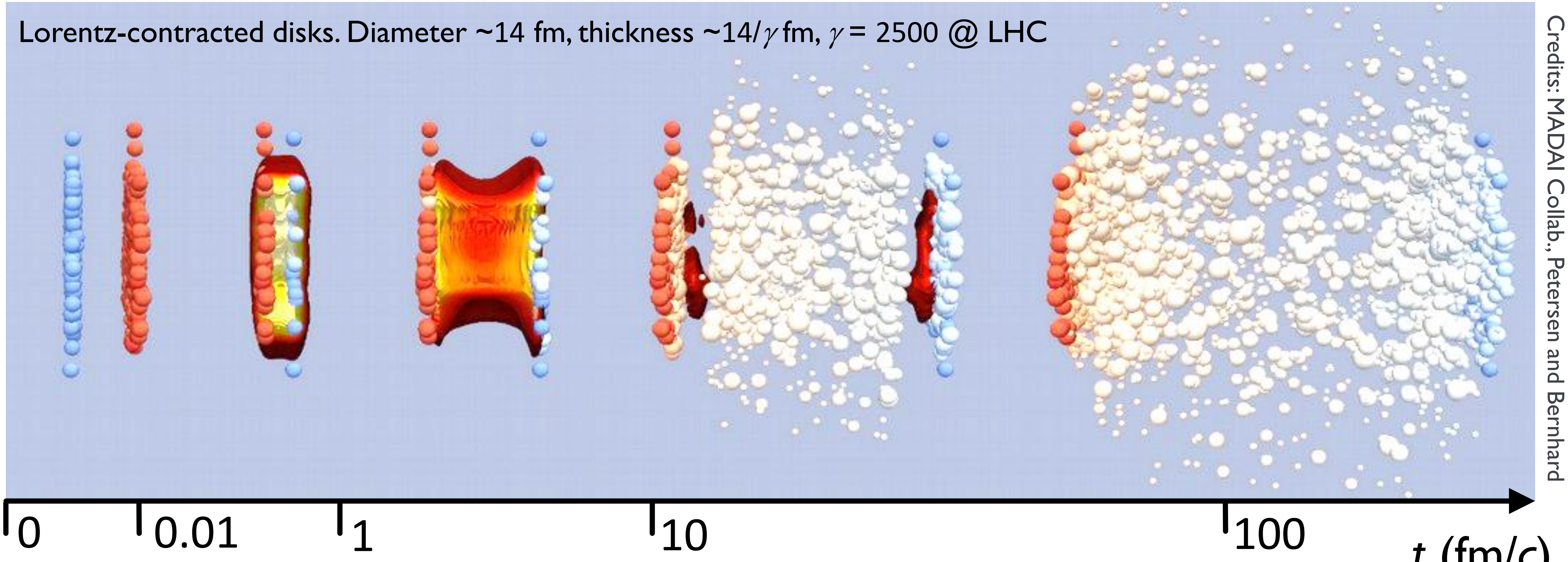
ALICE Collab., Physics Letters B 754 (2016) 235–248

- Excess at low p_T < 4 GeV/c wrt pQCD predictions related to thermal photons.
- Excess yield fitted with exponential $\propto \exp(-p_T/T_{eff})$.
- T_{eff} reflects an effective temperature average of the different temperatures during the space-time evolution of the medium.
- Caveat: blueshift due to radial flow has to be taken into account.

T_{eff} (0-20%) = (297 ± 12 stat ± 41 syst) MeV

T_{eff} (20-40%) = (410 ± 84 stat ± 140 syst) MeV

COLLISION EVOLUTION



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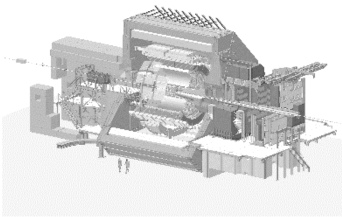


NUCLEAR MODIFICATION FACTOR PROBES THE MEDIUM

$$R_{AA}(p_T) = \frac{1}{< N_{coll} >} \times \frac{d^2N_{AA}/dp_Td\eta}{d^2N_{pp}/dp_Td\eta}$$

N_{coll}: Total number of nucleon pairs that collide, assuming transparency of the collision

Is a nucleus-nucleus collision a superposition of NN collision?

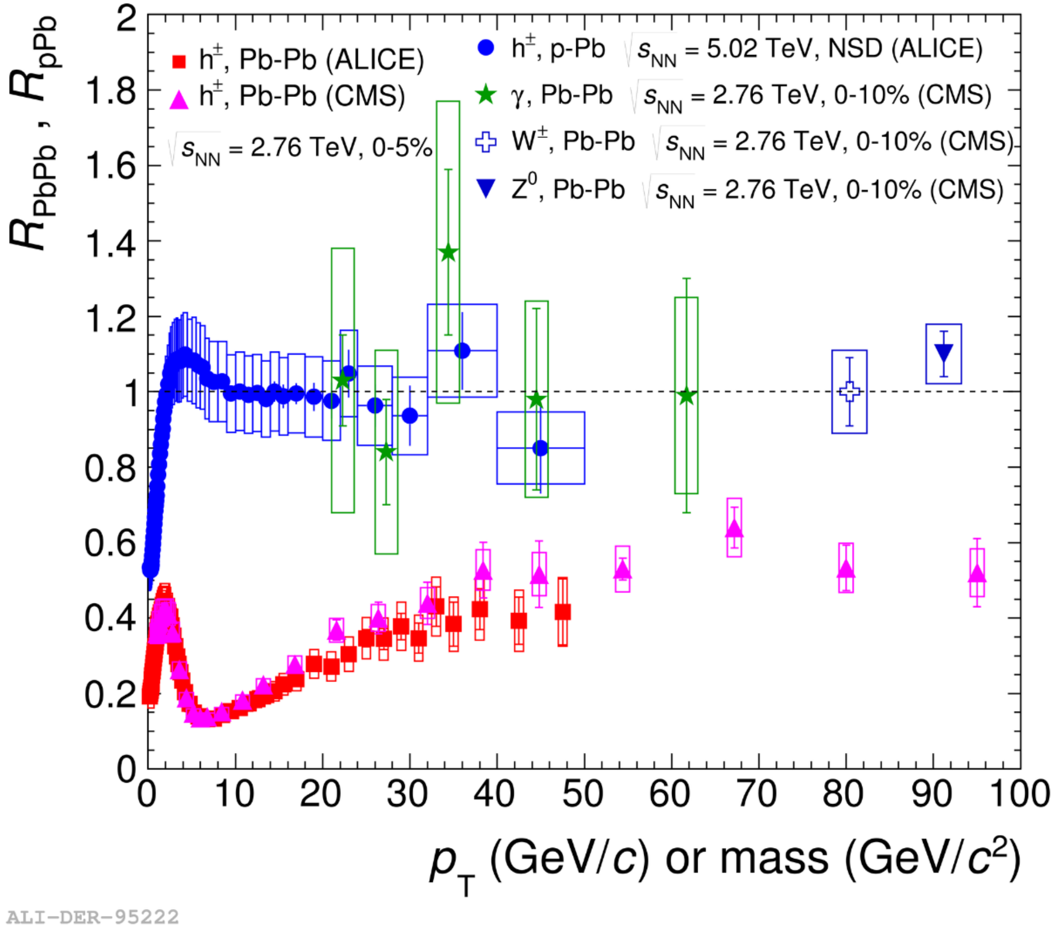
✓ If yes → R_{AA} = 1

Non-strongly interacting particles are not affected by the QGP

→ Photons, $W^{\pm}$ and Z^0 bosons R_{AA} = 1

Quarks and gluons lose energy in the QGP

→ Charged particles R_{AA} < 1



Nch p-Pb:ALICE, PRL110 (2013) 082302
Nch Pb-Pb:ALICE, PLB720 (2013) 52
Nch Pb-Pb: CMS, EPJC (2012) 72
γ: CMS, PLB 710 (2012) 256
$W^{\pm}$, CMS, PLB 715 (2012) 66
Z^0, CMS, PRL 106 (2011) 212301

C. Jahnke – 16/10, 16:05

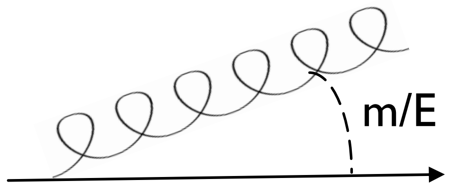
In-medium energy loss - consequence of collisional and radiative processes

→ Depends on QGP density

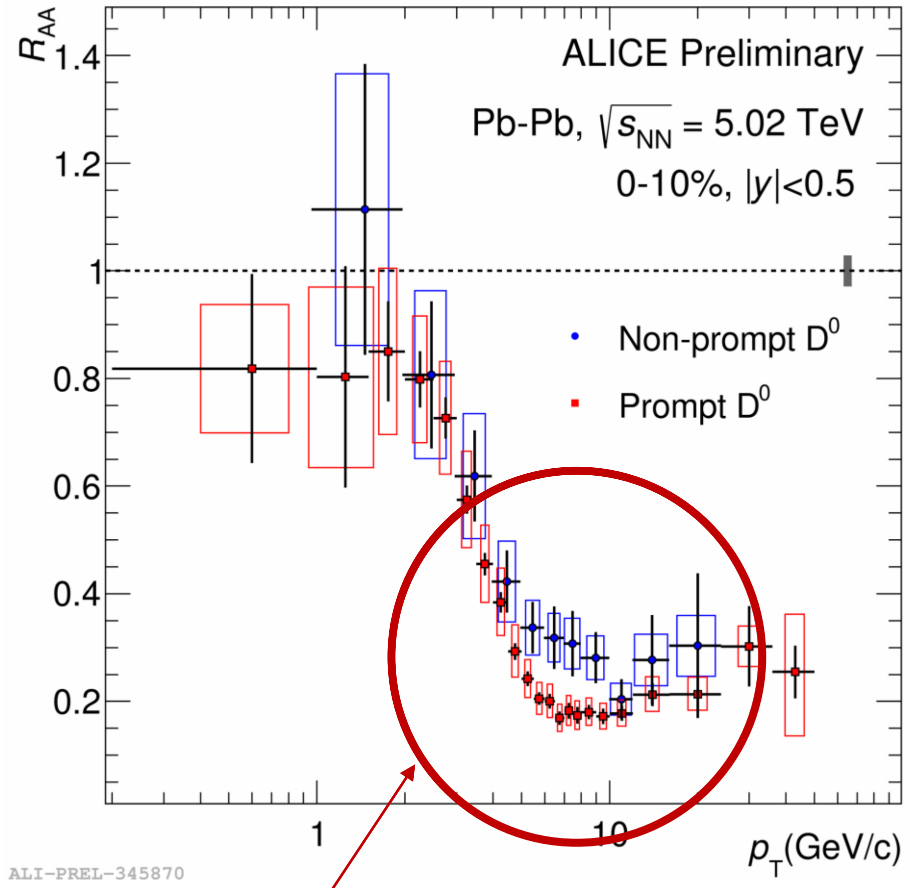
→ Depends also on quark mass

Gluon radiation is suppressed at angles smaller than the ratio of quark mass *m* to energy *E* ('dead-cone effect')

Eloss (light) > Eloss (charm) > Eloss (bottom)



Yu. L. Dokshitzer and D. E. Kharzeev, Phys. Lett. B 519 (2001) 199–206

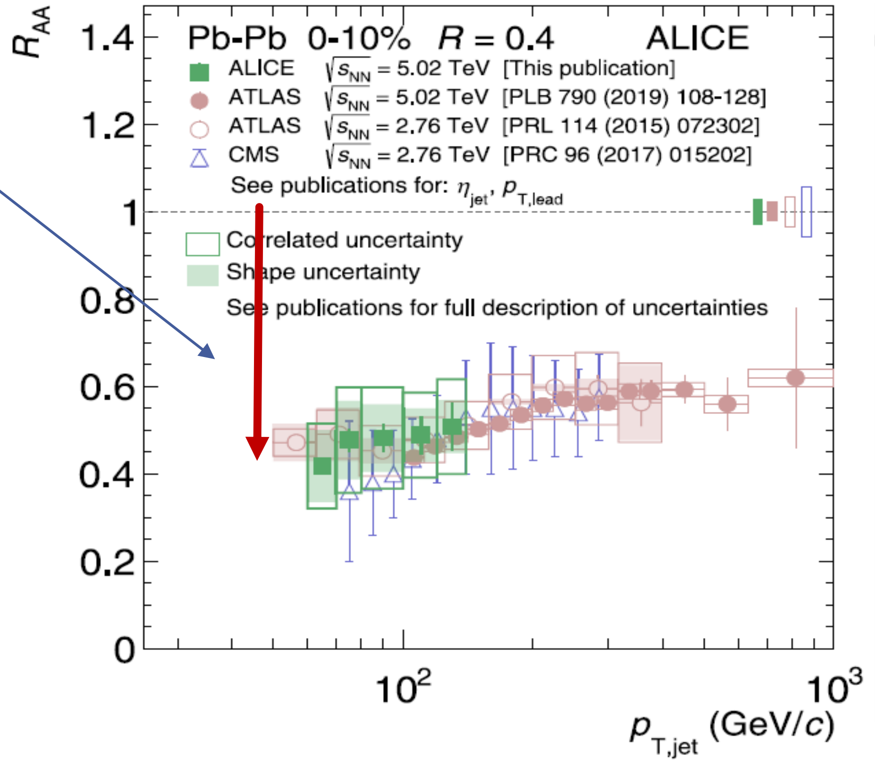


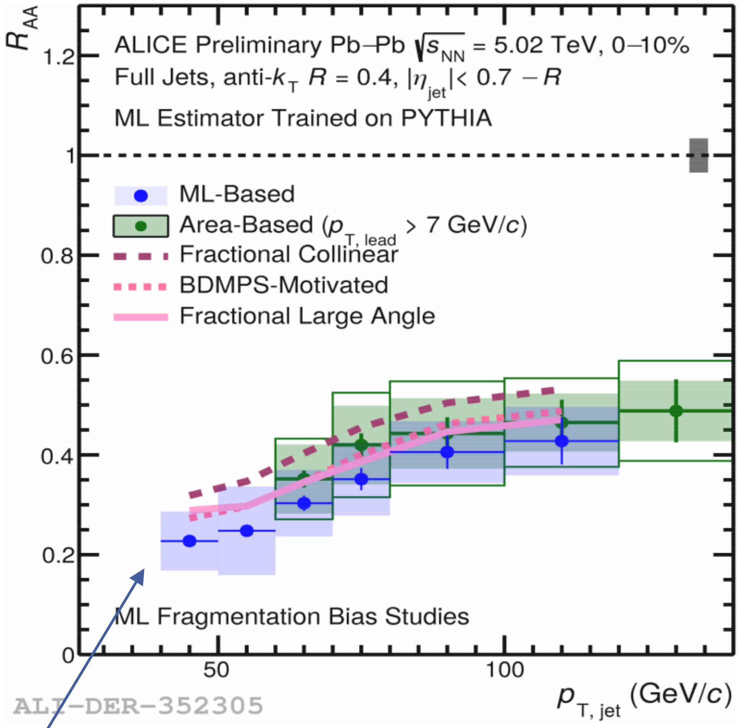
➡ Less suppression for (nonprompt) D from B decays than prompt D mesons

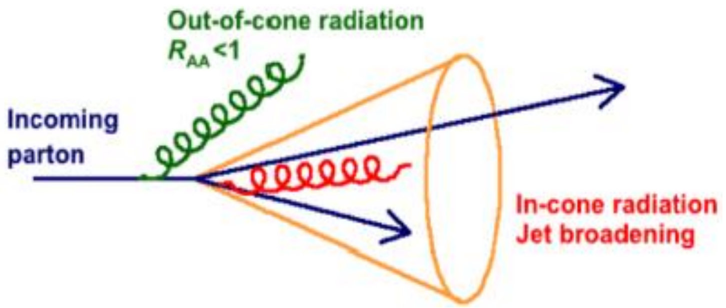
IN-MEDIUM ENERGY LOSS STUDIED WITH JETS R_{AA}

- Reduction of jet yields (R_{AA} ~ 0.3-0.4) down to 50 GeV/c
- Energy radiated outside the jet cone → QCD-induced gluon emission at larger angles?

Phys. Rev. C **101**, 034911 (2020)







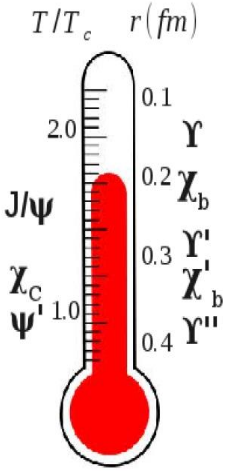
Jet measurements extended to lower jet p_T and large R using machine learning (ML)

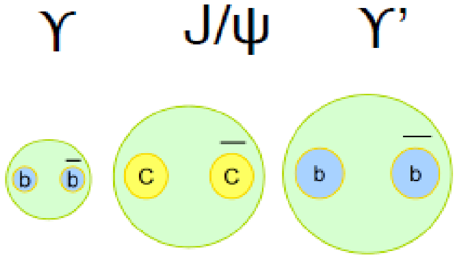
QUARKONIA ARE SUPPRESSED

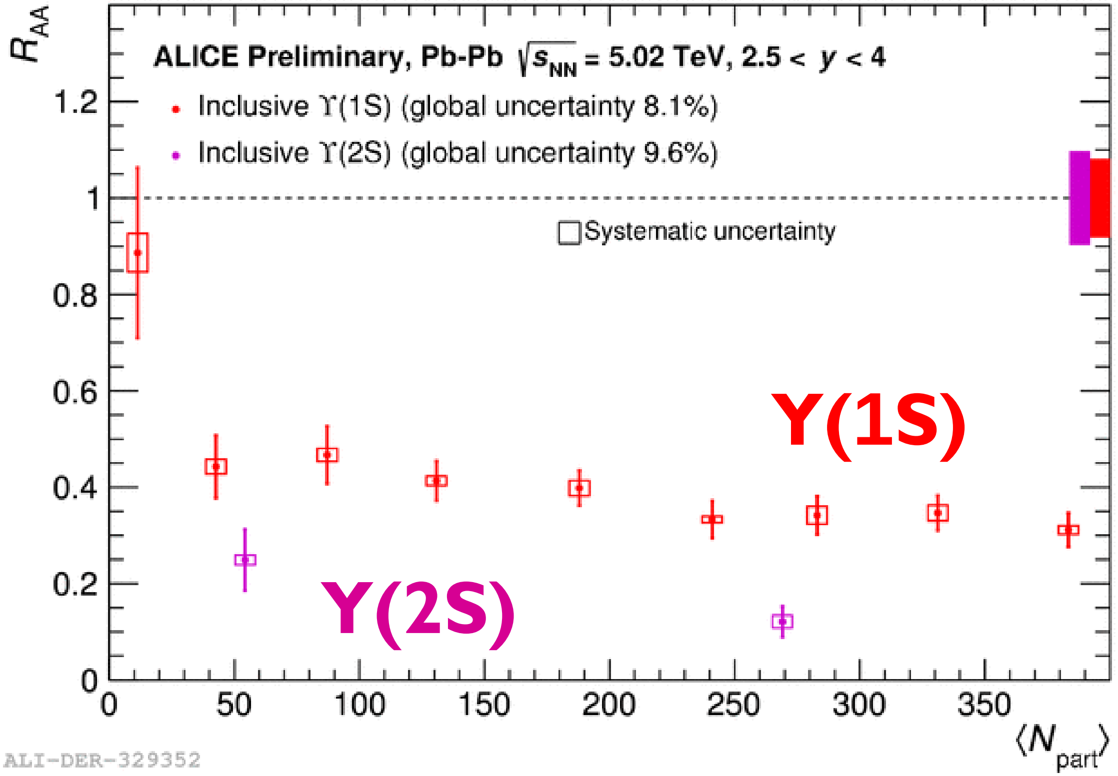
- Quarkonia are suppressed due to screening of the quark color charge in the QGP

  T. Matsui and H. Satz, Phys. Lett. B **178** (1986) 416

- Sequential suppression of quarkonia, depending on their sizes



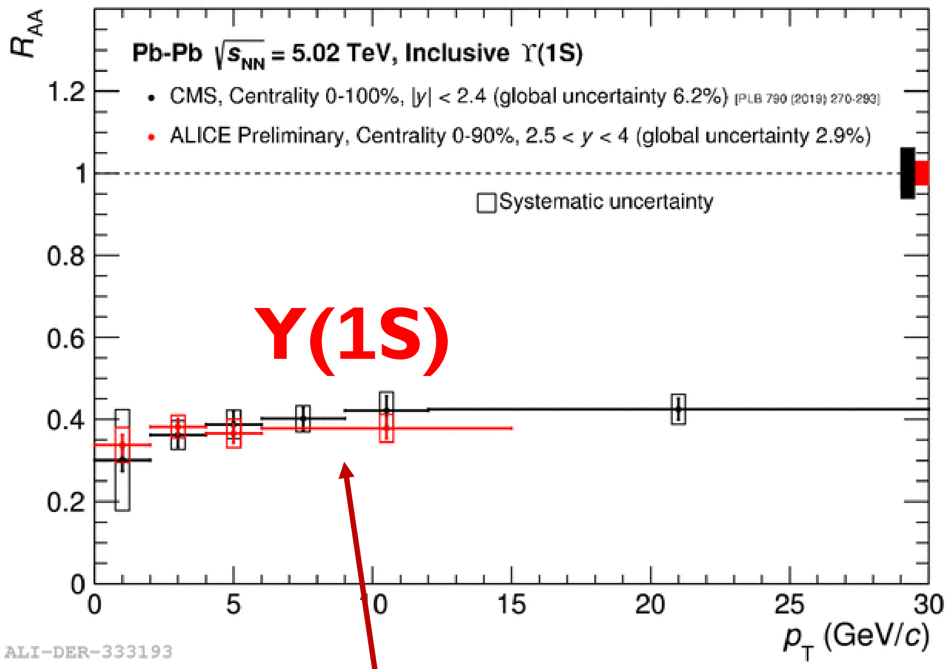


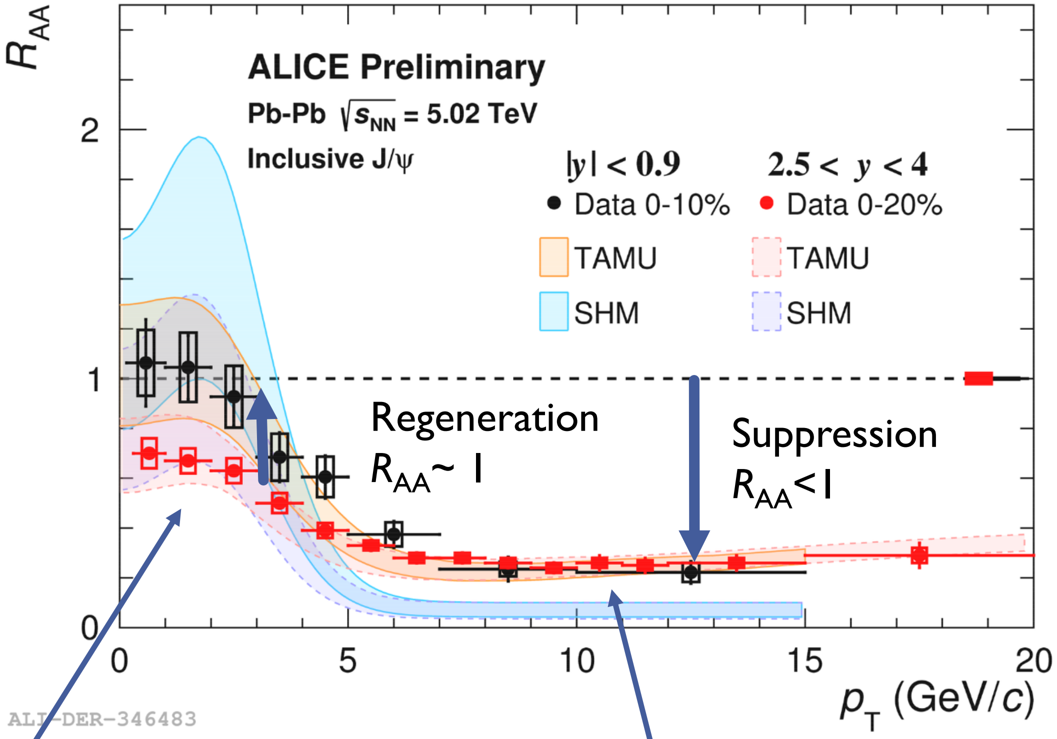


Y(2S) more suppressed than **Y(1S)**

QUARKONIA ARE SUPPRESSED AND REGENERATED

Regeneration rate due to medium interactions ~ to the square of the # of heavy-quark pairs





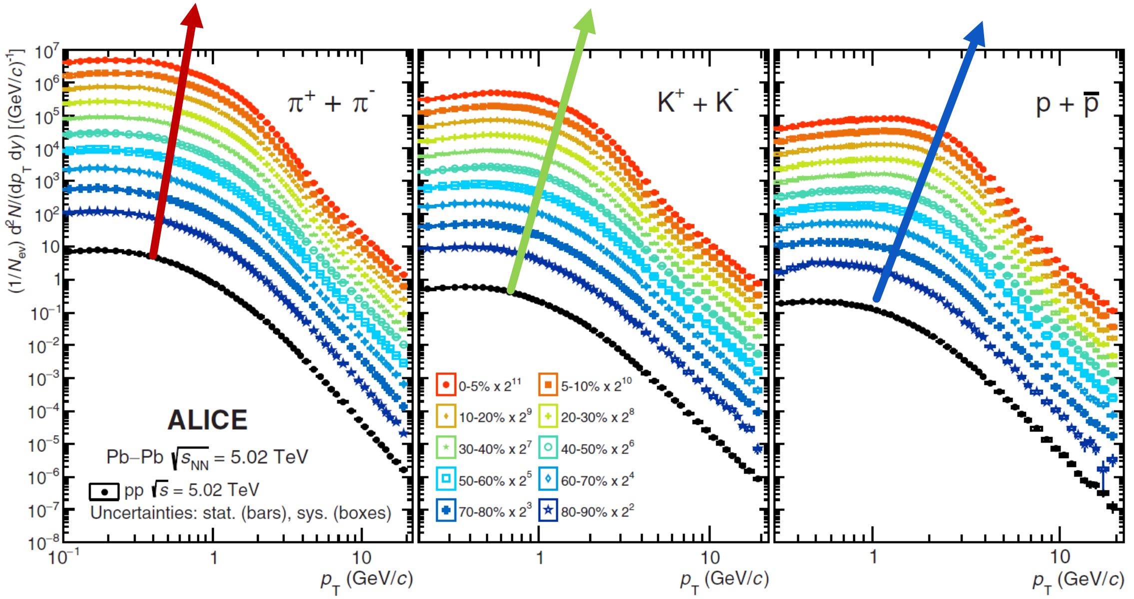
Negligible regeneration effect for bottomonia

Charmonia regenerated at low p_T < 6 GeV, effect more pronounced at mid-rapidity

Strong J/ψ suppression at high p_T, with negligible y dependence

HYDRODYNAMICS OF THE MEDIUM: RADIAL FLOW

Phys. Rev. C **101**, 044907 (2020)



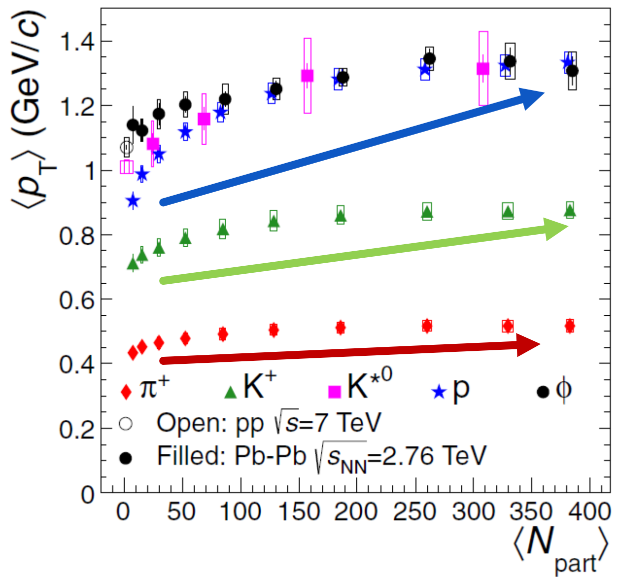
- Combined Blast-wave fit of spectra
- For each centrality a common set T_{kin}, β_T

$$E\frac{d^3N}{dp^3} \propto \int_0^R m_T I_0\left(\frac{p_T \sinh(\rho)}{T_{kin}}\right) K_1\left(\frac{m_T \cosh(\rho)}{T_{kin}}\right) r\,dr.$$

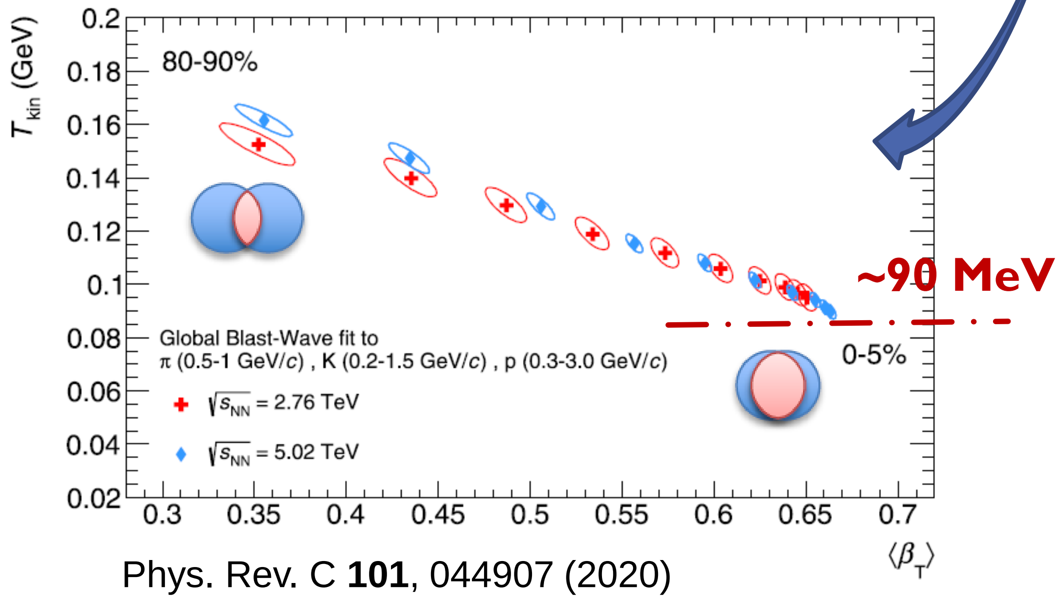
$$\rho = \tanh^{-1}\beta_T = \tanh^{-1}\left[\left(\frac{r}{R}\right)^n \beta_s\right]$$

Mass-dependent **hardening of spectra**

- More evident effect in central collisions
- ϕ and K* follow the same trend as protons



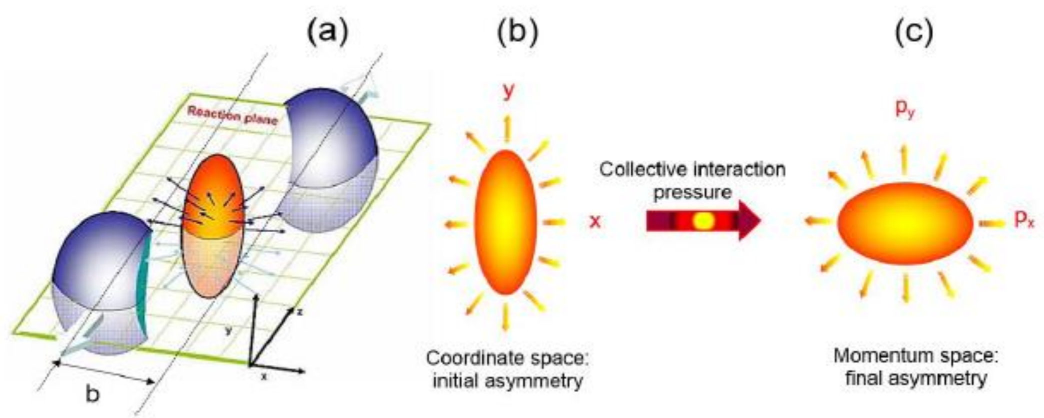
Phys. Rev. C **91**, 024609 (2015)



Phys. Rev. C **101**, 044907 (2020)

HYDRODYNAMICS OF THE MEDIUM: ANISOTROPIC FLOW

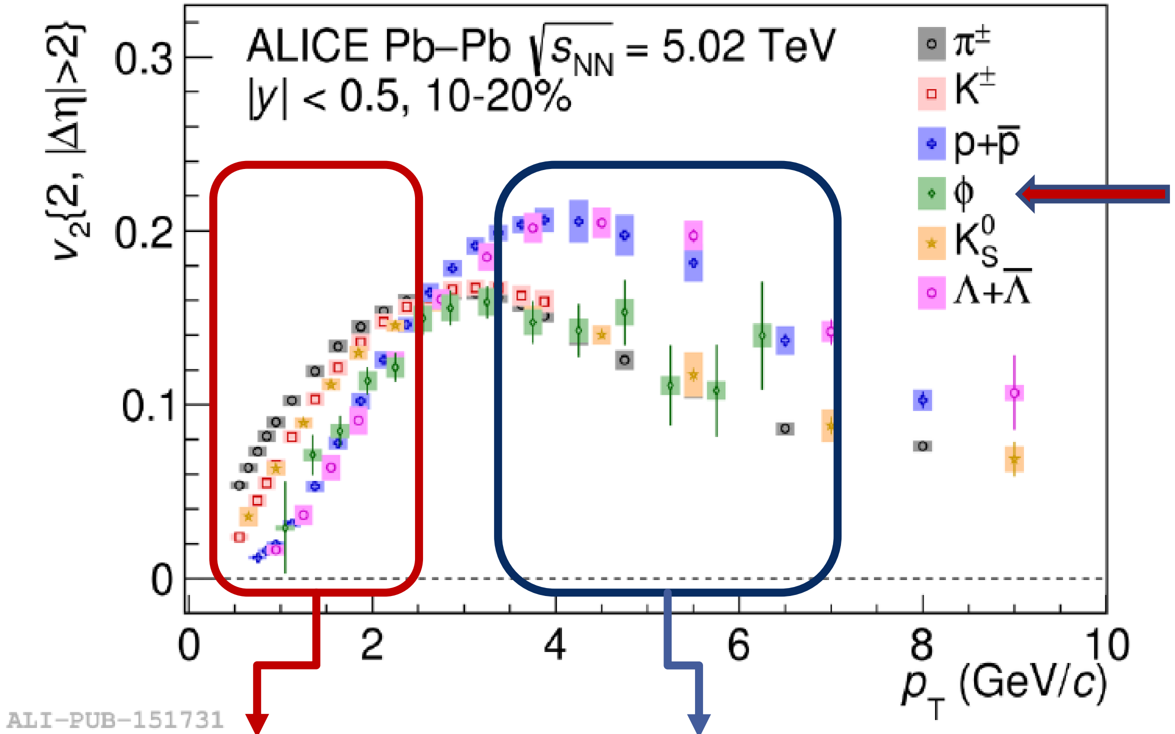
Anisotropies in the initial energy density distribution lead to azimuthal anisotropies in particle production



- Depends on EOS, η/s and ζ/s
- Measured via Fourier expansion

$$\frac{\mathrm{d}N}{\mathrm{d}\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \psi_n)]$$

ALICE, JHEP 09 (2018) 006



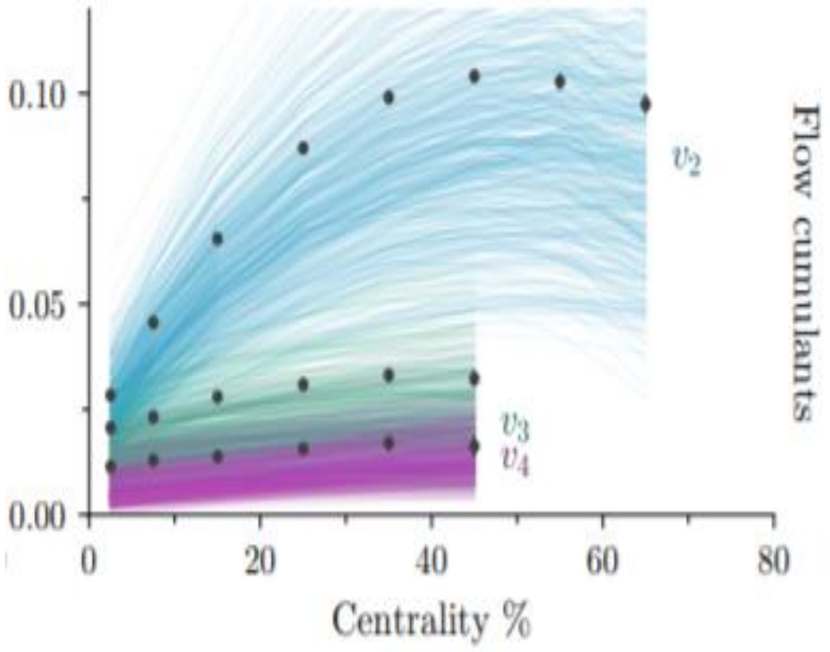
Mass ordering (higher mass → lower v_2): interplay between radial and elliptic flow

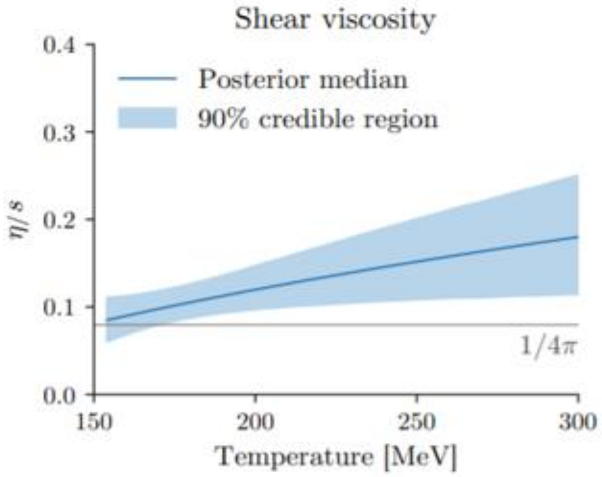
Higher n_q higher v_2 → quark coalescence as dominant particle production mechanism

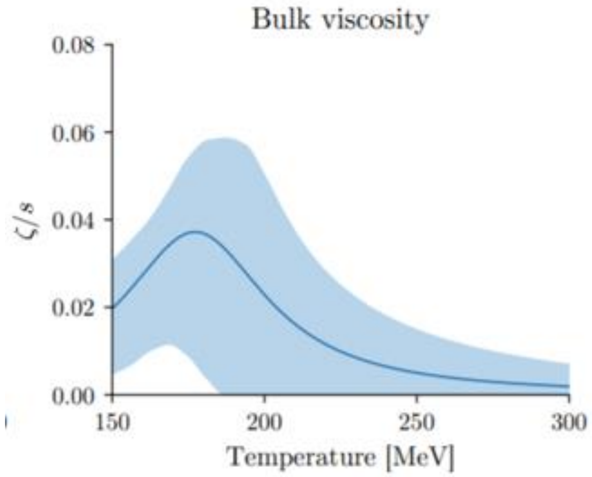
HYDRODYNAMICS OF THE MEDIUM

Use high-precision data to estimate the properties of the QGP fluid with a Bayesian procedure

Use not only flow coefficients, also mean p_T, spectra, ...





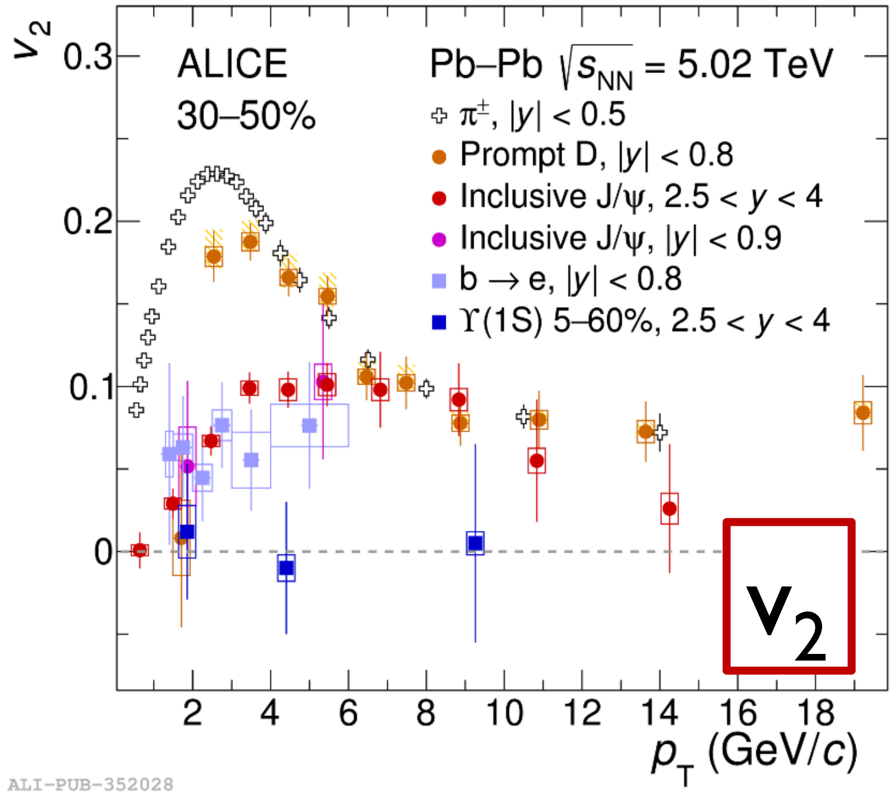


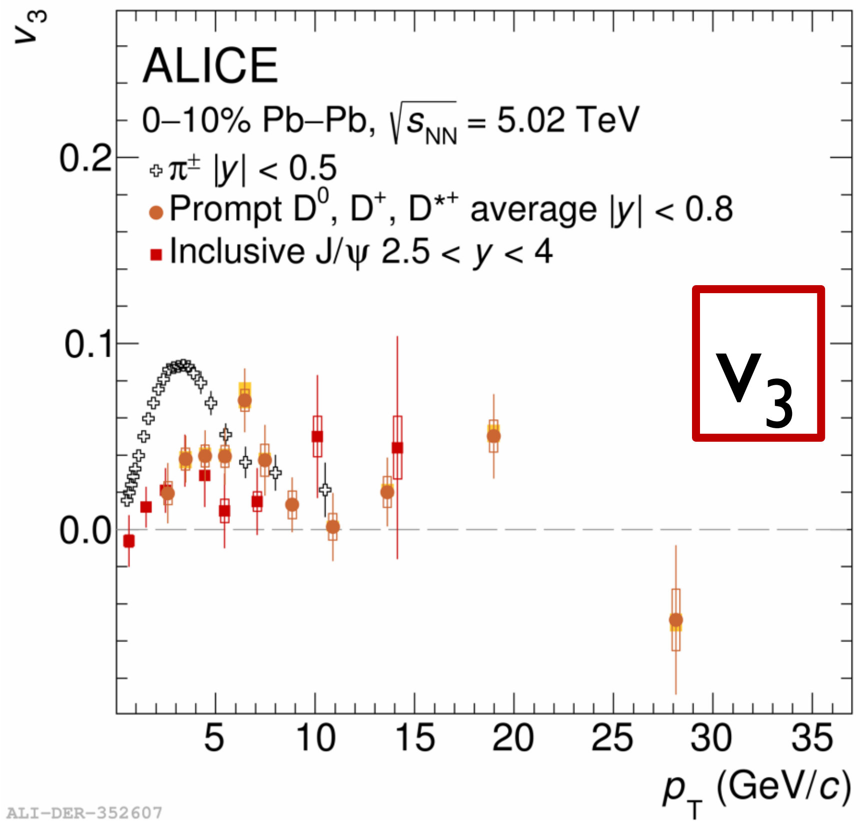
J.E. Bernhard, J.S. Moreland, and S.A. Bass, Nat. Phys. **15,** 1113 (2019)

CHARM AND BEAUTY FLOW

C. Jahnke – 16/10, 16:05

Charm quarks take part in the collective expansion of the medium





J/ψ: arXiv:2005.14518

π: JHEP 09 (2018) 006

D: arXiv:2005.11131

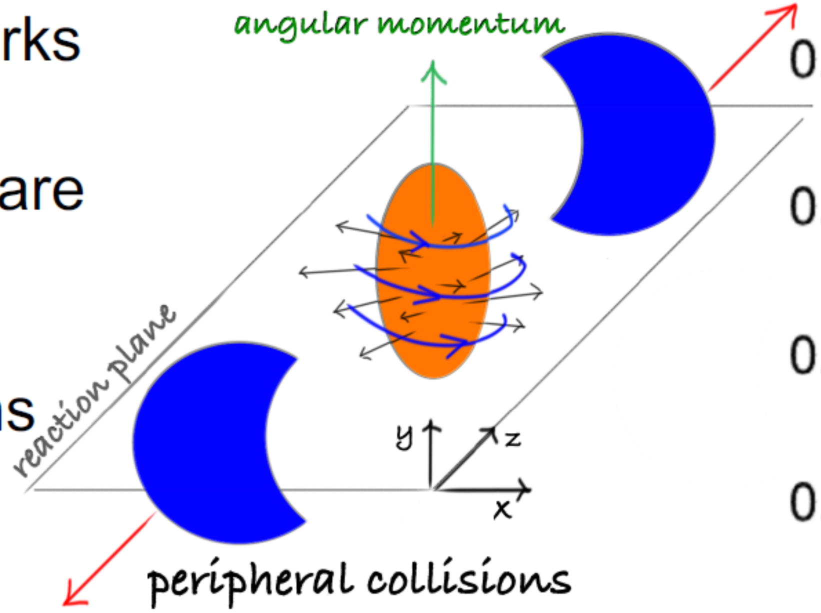
ϒ(1S) PRL 123, 192301 (2019)

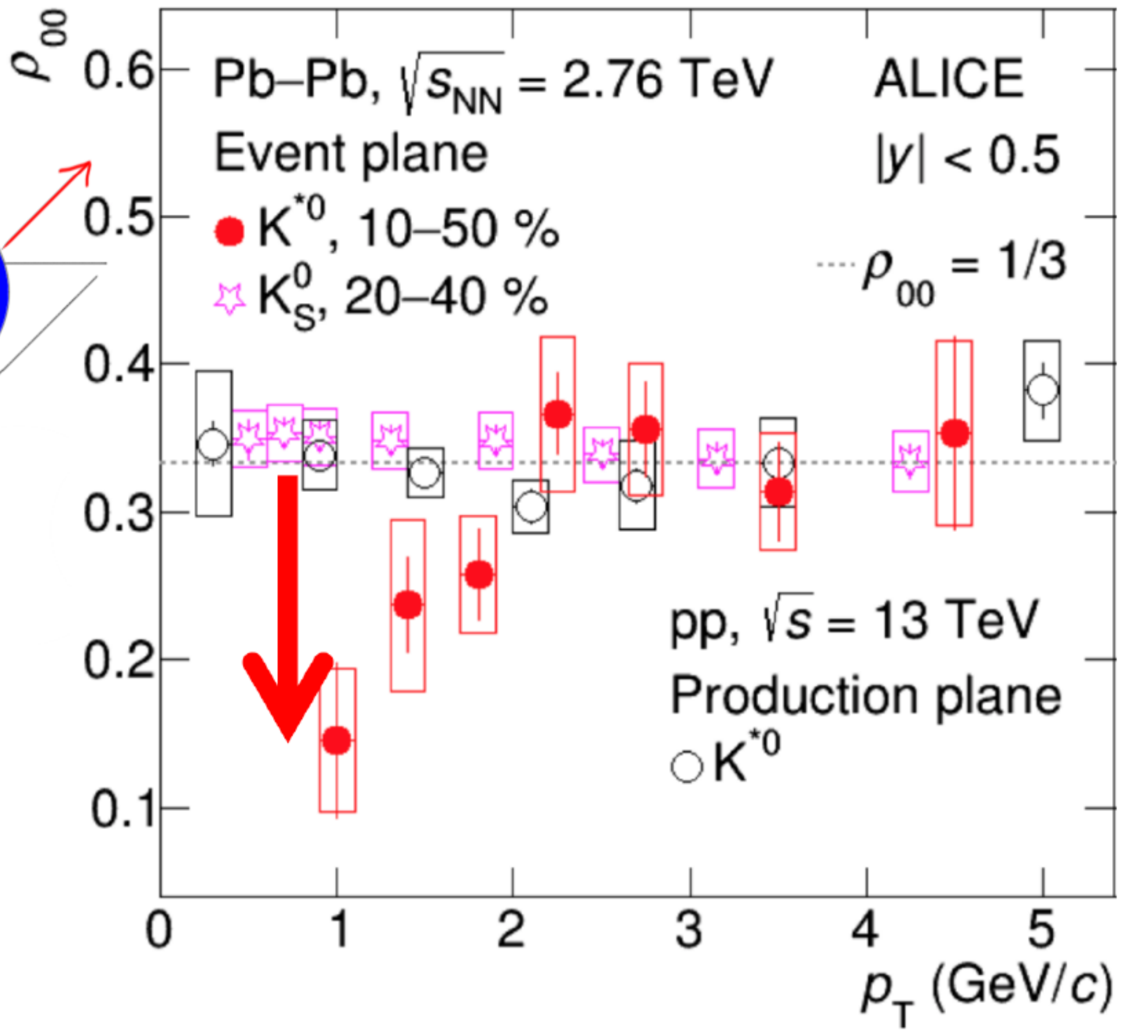
- Positive v_2 and v_3 of D mesons and J/ψ → consistent with recombination of flowing c quarks
- Open beauty v_2 > 0 while bottomonium v_2 ~ 0

POLARIZATION OF VECTOR MESONS

QGP in Pb-Pb → high angular momentum equivalent to the order of 10^{21} revolutions/s

- polarises the quarks
- if vector mesons are produced via recombination → their spin aligns $\rho_{00} < 1/3$

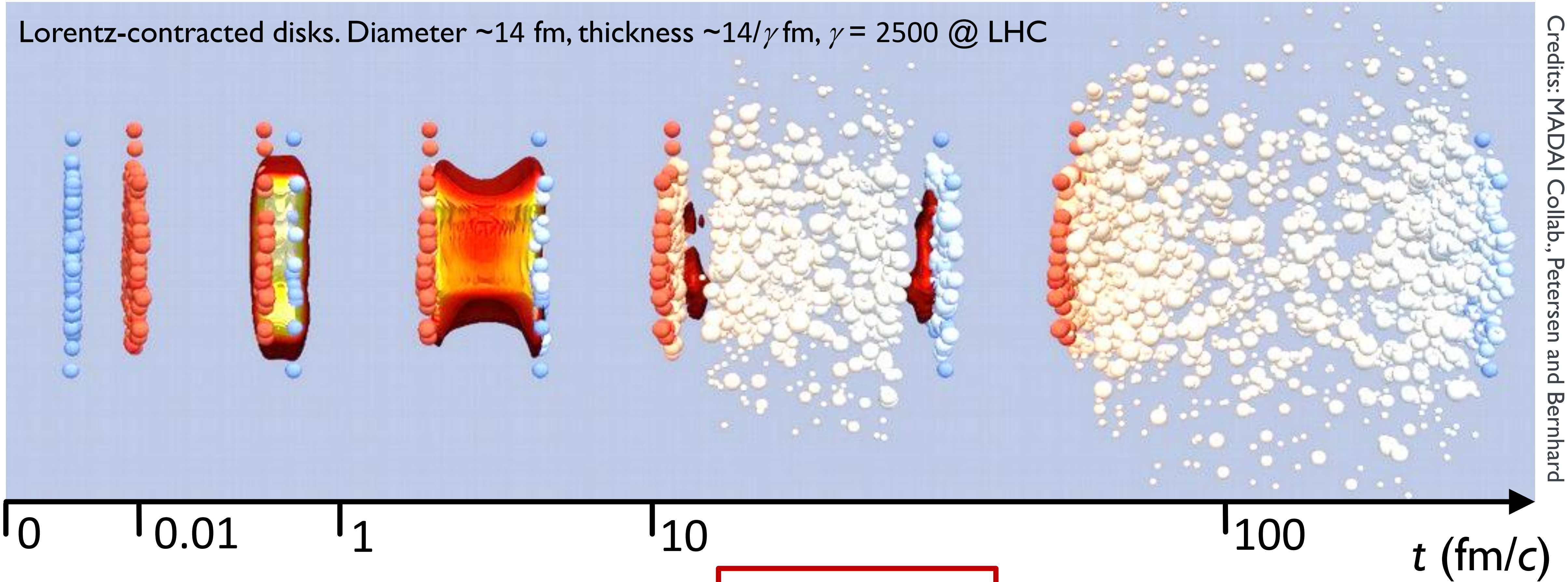




➢ measurement using K^{*0}
→ 3σ effect at low p_T

ALICE, Phys.Rev.Lett. 125 (2020) 1, 012301

COLLISION EVOLUTION



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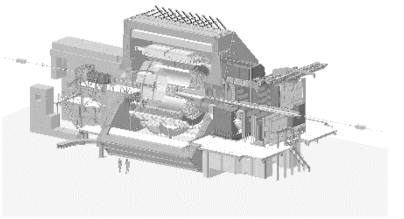
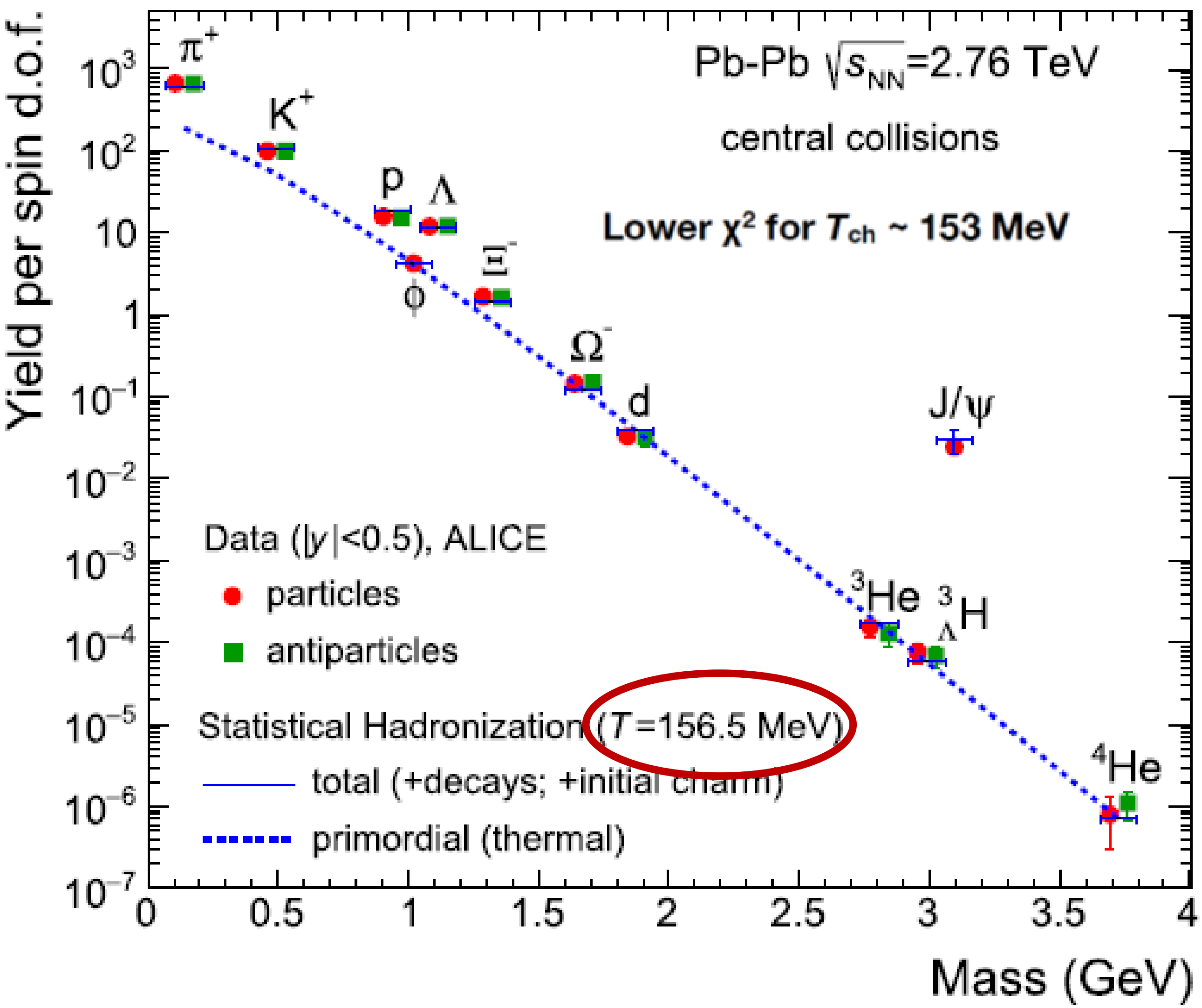


TEMPERATURE AT HADRONIZATION FROM PARTICLE ABUNDANCES

Statistical Hadronization Model (SHM)



A.Andronic et al., Physics Letters B 797 (2019) 134836

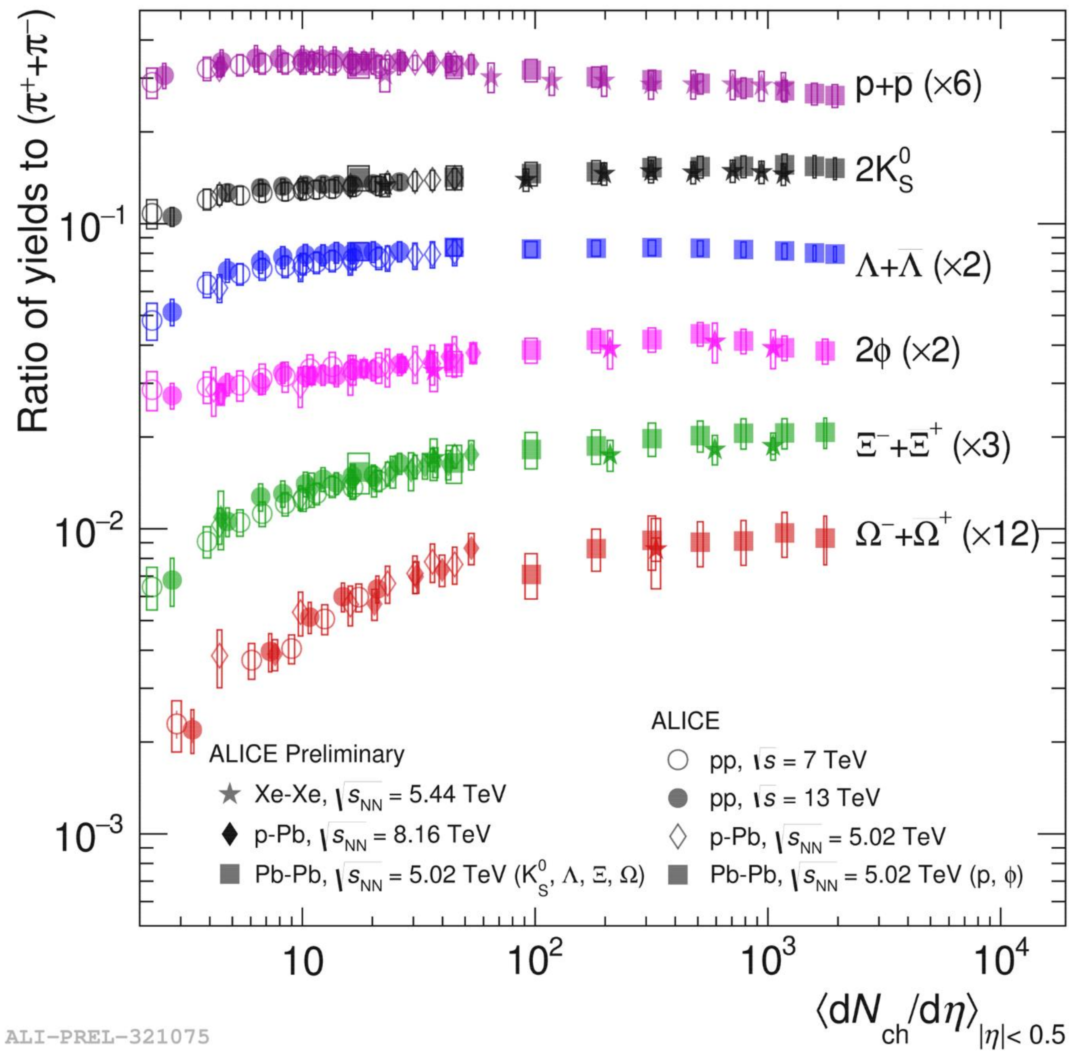
- At hadronization fireball is close to thermal equilibrium
- A rapid hadrochemical freeze-out takes place at the phase boundary
- Hadron abundances described by thermal SHM over 9 orders of magnitude!
- Note that also loosely bound objects (light nuclei and hyper-nuclei) and heavy-flavour hadrons (J/ψ) are described within SHM

Hyper-nuclei → A. Borissov – 14/10, 12:45

HADROCHEMISTRY: RELATIVE ABUNDANCES OF HADRONS

- **Smooth evolution of particle production from small to large systems** vs charged-particle multiplicity
- Strangeness production increasing with multiplicity until saturation (grand-canonical plateau) is reached
- Steeper increase for stranger particles
- High-multiplicity pp: same hadrochemistry as larger (p-Pb, peripheral Pb-Pb) systems
- **Common mechanism for all systems?**

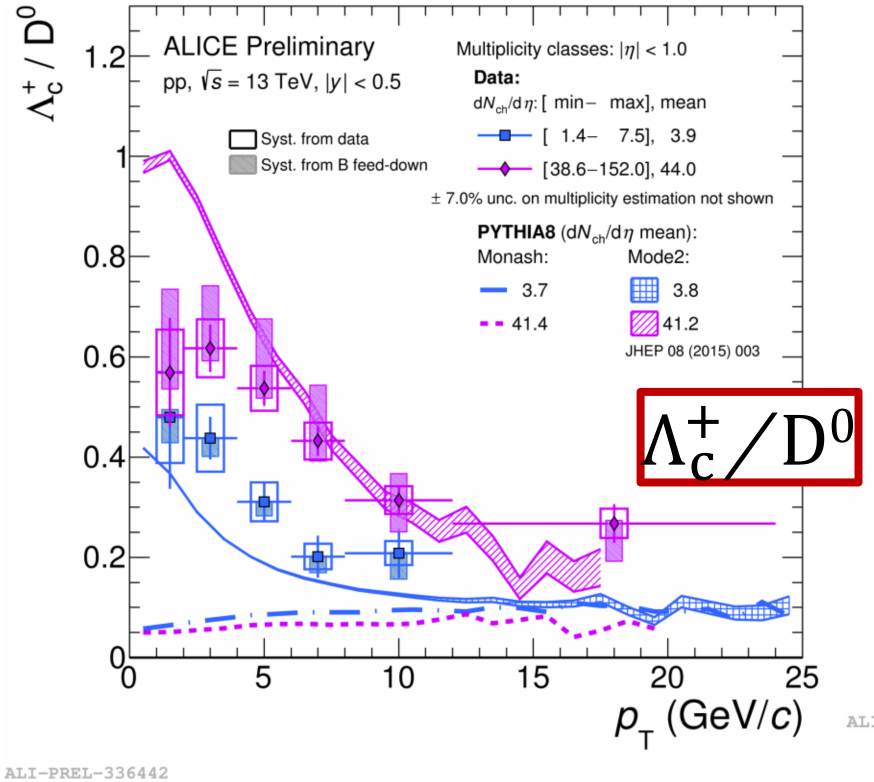
ALICE Collab., Nat. Phys **13,** 535–539 (2017)

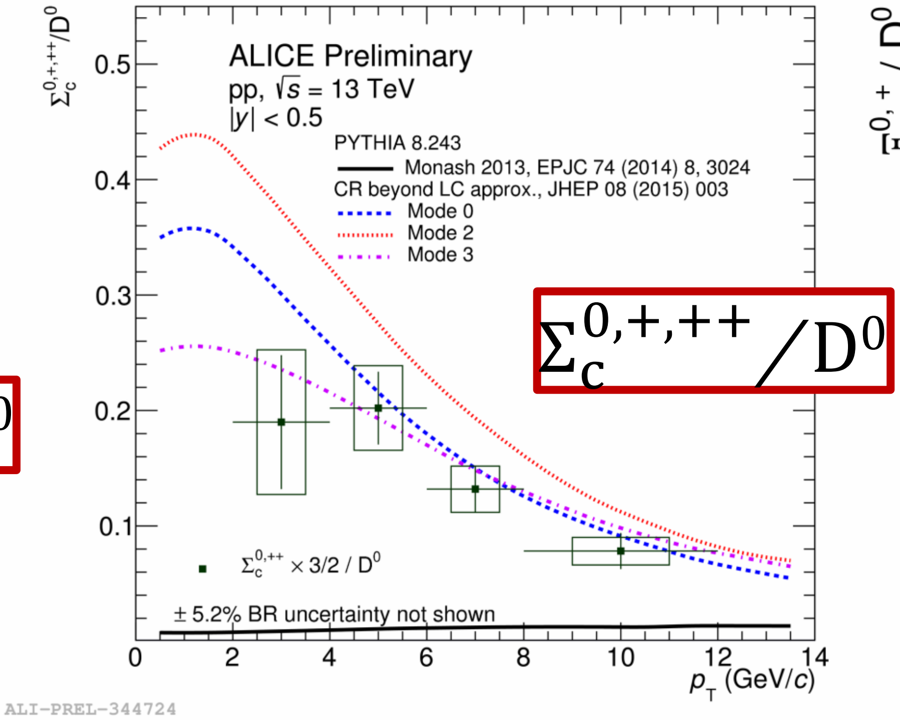


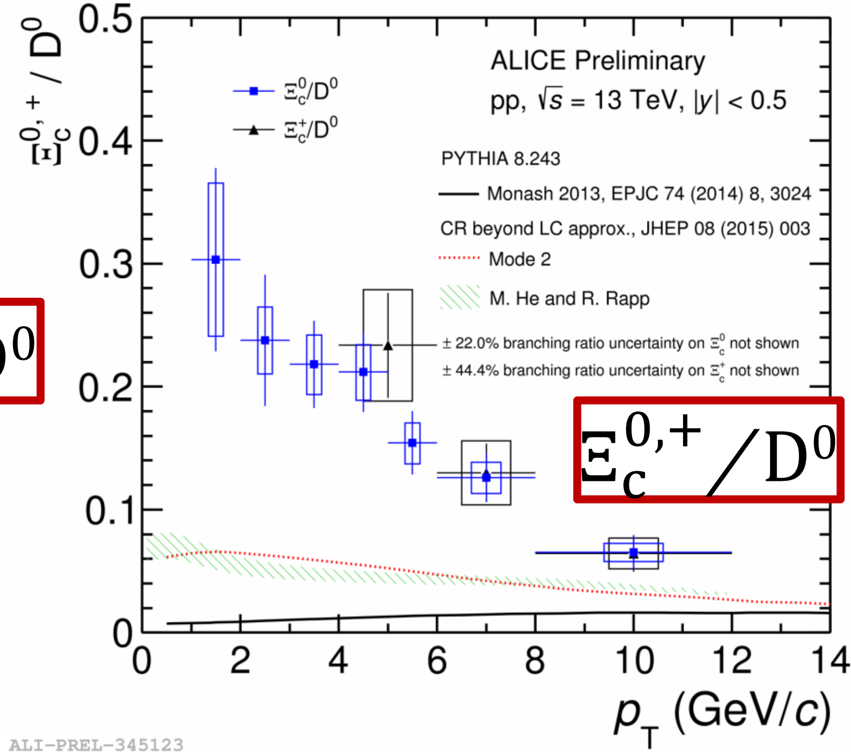
HEAVY QUARK HADRONIZATION

D. Peresunko – 12/10, 16:20

C. Jahnke – 16/10, 16:05

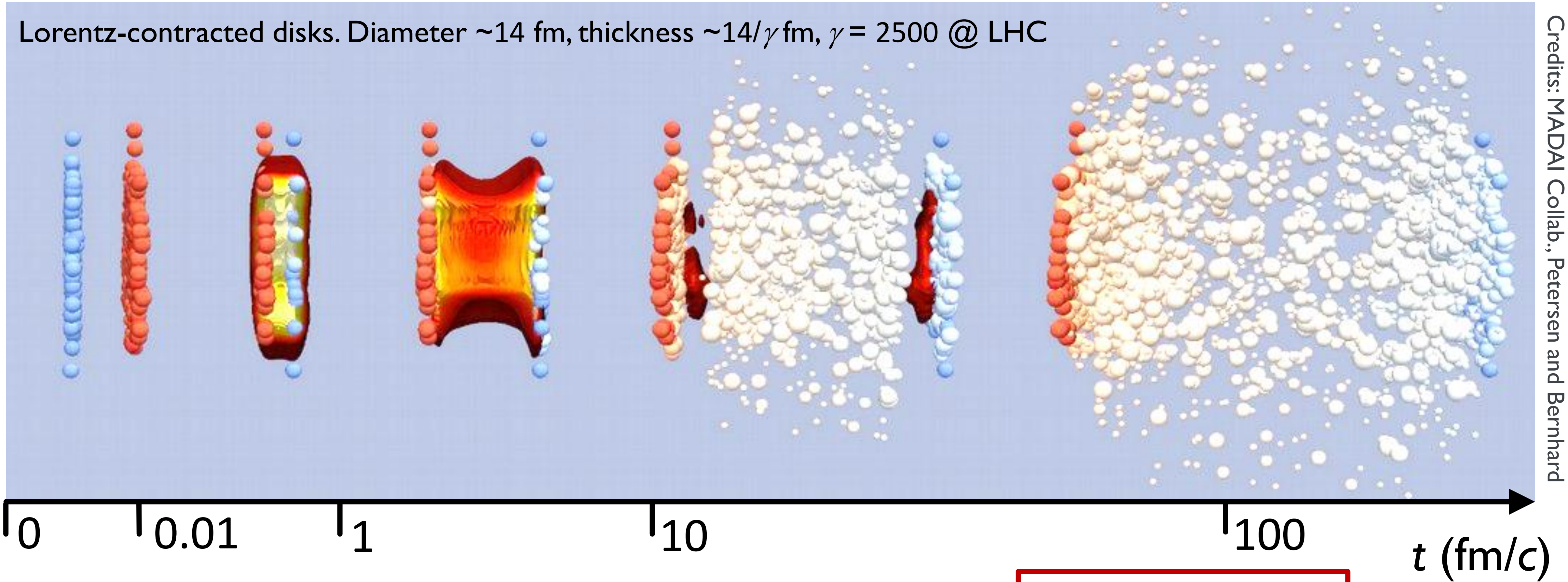






- Fraction of c quarks going to baryons is much larger than in e^+e^- collisions
- Multiplicity dependent baryon-to-meson ratio observed
- Enhancement of baryon-to-meson ratios in charm sector at low p_T
- Ratio described by PYTHIA w/ color reconnection but not for Ξ_c

COLLISION EVOLUTION



Credits: MADAI Collab., Petersen and Bernhard

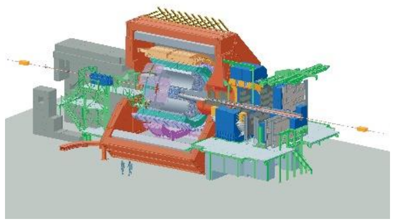
Initial stage
nPDF,
saturation,
shadowing

Gluon and
quark-pair creation
All heavy quarks
created at this stage

QGP: deconfined
nuclear matter
expanding
hydrodynamically

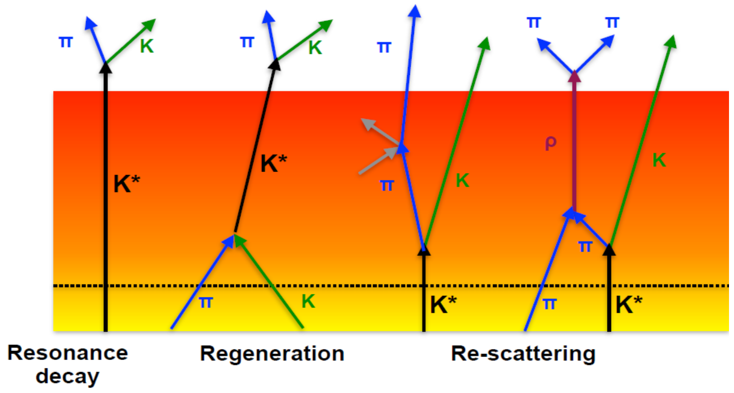
Hadronization and
chemical freeze-out
Inelastic collisions
cease

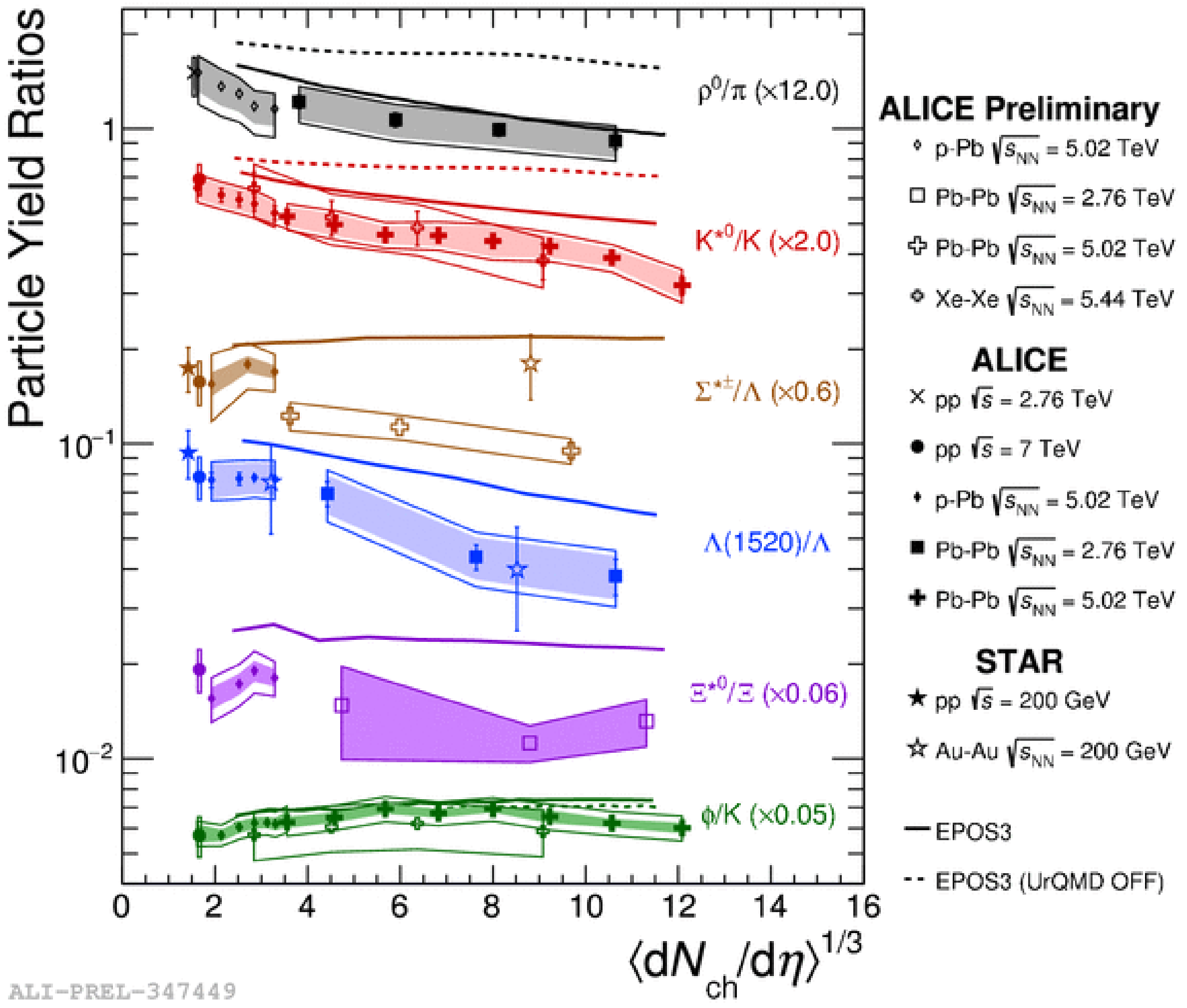
Kinetic freeze-out
Elastic collisions cease
Free streaming particles
to the detectors



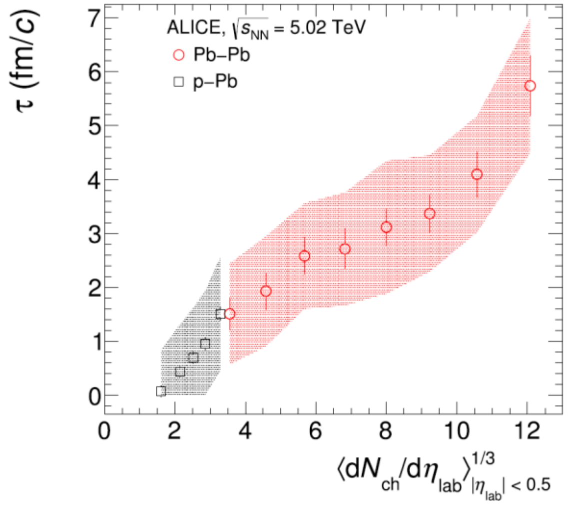
LIGHT-FLAVOUR RESONANCES PROVES THE LATE HADRON PHASE

Resonances have **lifetimes similar to the lifetime of the hadron phase** → they are subject to regeneration and re-scattering effects





Estimate the duration between chemical and kinetic freeze-out

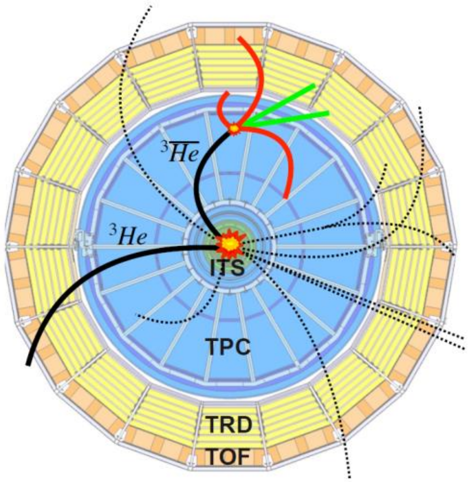


Phys. Lett. B 802 (2020) 135225

Resonance lifetime(fm/c): ρ(1.3)<K*(4.2)<Σ*(5.5)<Λ*(12.6)<Ξ*(21.7)<ϕ(46.4)

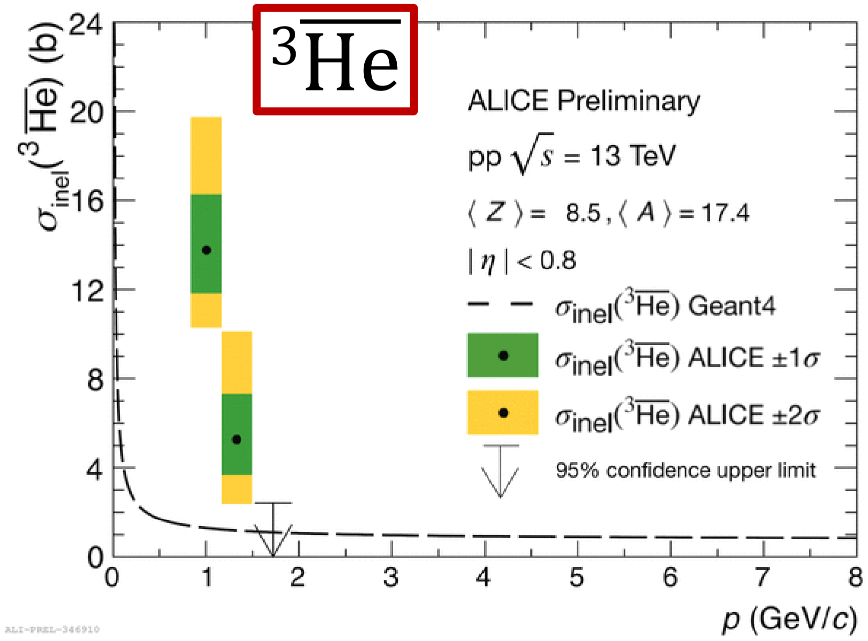
BEYOND HEAVY-ION PHYSICS: A LABORATORY FOR QCD STUDIES

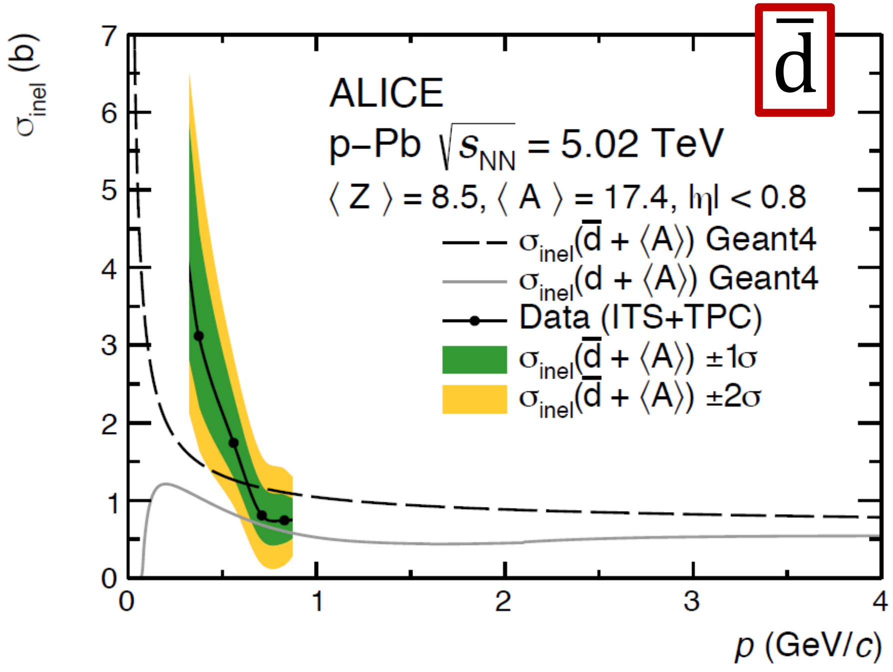
ANTINUCLEI ABSORPTION STUDIES



Antinuclei (A≥2) inelastic interaction cross sections are not well constrained

- Important for indirect Dark Matter searches
- Source of systematic uncertainty for the production cross sections

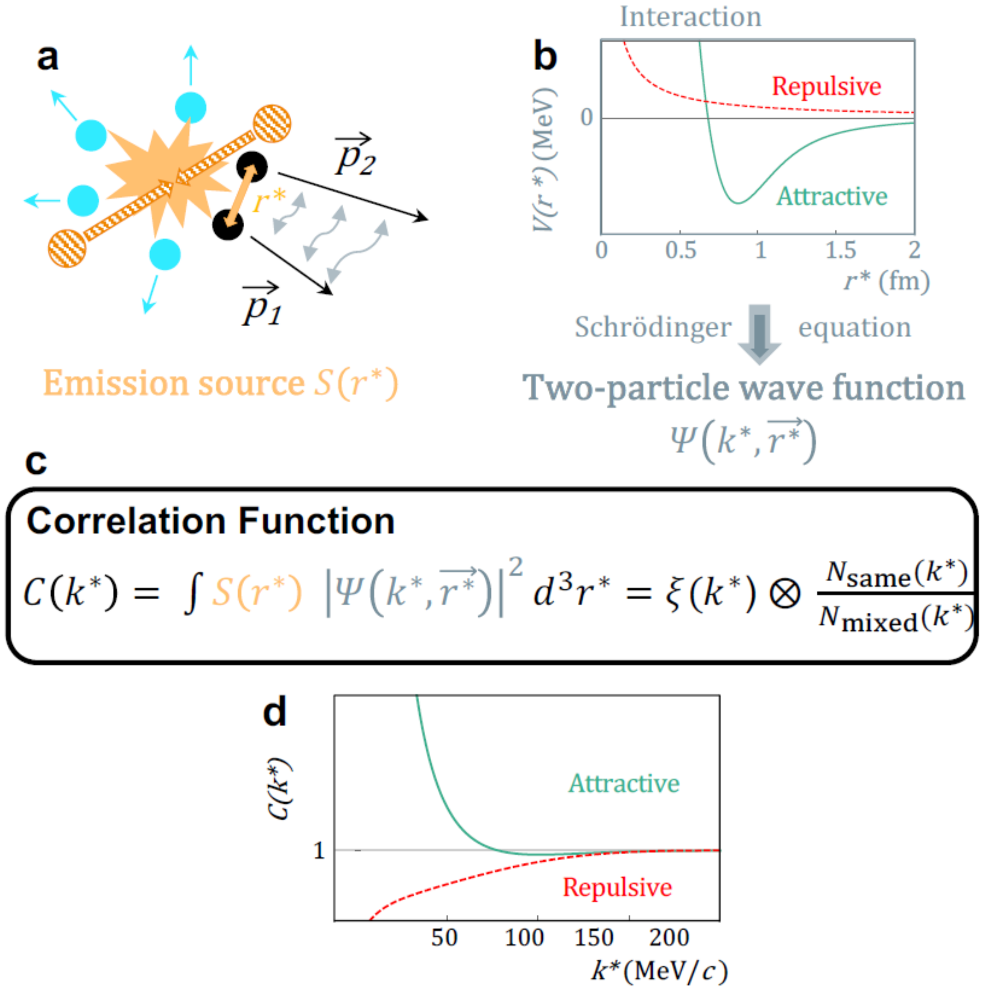


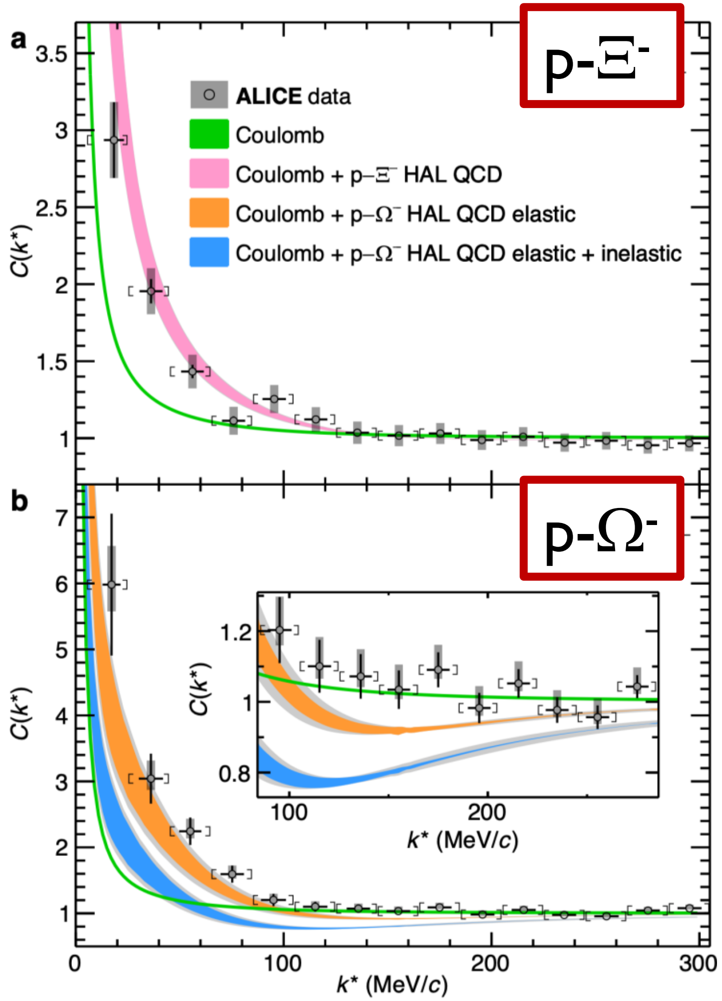


arXiv:2005.11122

PROTON-HYPERON INTERACTIONS

Proton-hyperon strong interaction poorly known





arXiv:2005.11495

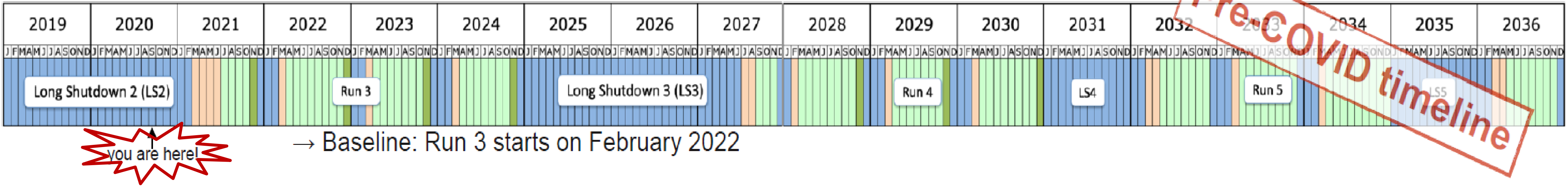
First precise observation of attractive strong interaction between p and Ξ^- or Ω^-

More to come in Run 3: d-Λ, p-Σ, Ω-Ω

THE FUTURE: RUN3 AND RUN4 AND BEYOND

THE FUTURE: RUN 3 AND RUN 4 AND BEYOND

Run 3: $\mathcal{L}_{Pb\text{-}Pb} = 6.0\ nb^{-1}$ Run 4: $\mathcal{L}_{Pb\text{-}Pb} = 7.0\ nb^{-1}$



→ Baseline: Run 3 starts on February 2022

Detector upgrade

- In LS2, all-pixel Inner Tracking System, GEM-based TPC readout, Pixel Muon Forward Tracker
- Improved tracking resolution down to low p_T
- In LS3, New cylindrical inner tracker and high-granularity Forward Calorimeter

Data taking strategy

- Read out all Pb-Pb interactions up to maximum collision rate of 50 kHz → increase Run 2 minimum-bias sample by factor 50-100

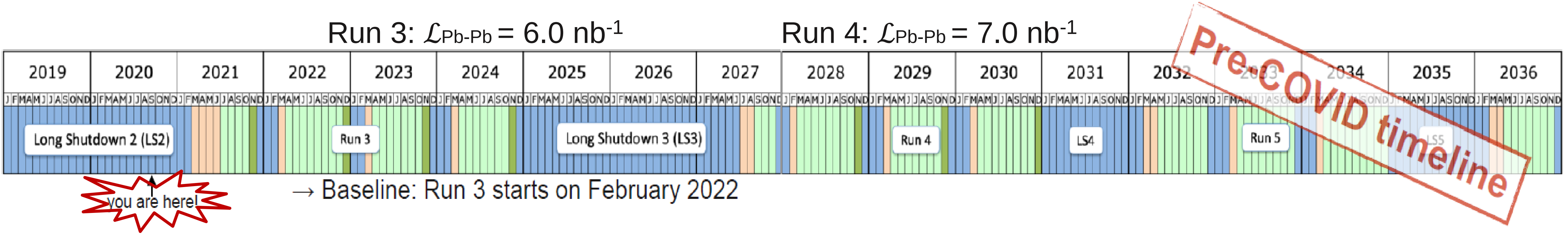
W. Trzaska – 14/10, 11:35

G. Feofilov – 14/10, 12:10

M. Slupecki – 17/10, 11:25

THE FUTURE: RUN 3 AND RUN 4 AND BEYOND

Run 3: $\mathcal{L}_{\text{Pb-Pb}} = 6.0\ \text{nb}^{-1}$ Run 4: $\mathcal{L}_{\text{Pb-Pb}} = 7.0\ \text{nb}^{-1}$



→ Baseline: Run 3 starts on February 2022

Physics goals

- Heavy-flavour mesons and baryons (down to very low p_T) → mechanisms of quark-medium interaction
- Charmonium states → dissociation/regeneration as tool to study de-confinement and medium temperature
- Di-leptons from QGP radiation and low-mass vector mesons → χ symmetry restoration, initial temperature
- High precision measurement of light and hyper-nuclei → production mechanism and degree of collectivity

W. Trzaska – 14/10, 11:35

G. Feofilov – 14/10, 12:10

M. Slupecki – 17/10, 11:25

CONCLUSIONS AND OUTLOOK

Harvest from Run 1 + 2 offers:

- Detailed insights into QGP characteristics
- Fundamental advances in QCD at high density
- Contributions to astrophysics, hadron structure, …

Run 2 +3 and beyond:

- Major LS2 upgrade on track for pp in 2021
- In preparation: ITS3, FoCal in LS3
- Ambitious plans for Run 5+: the next generation